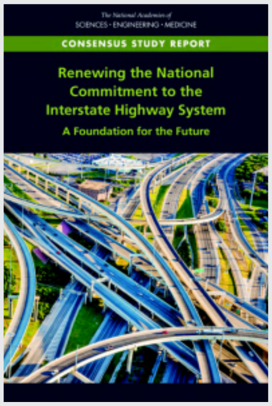

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Renewing the National Commitment to the Interstate Highway System

A Foundation for the Future

Committee for a Study of the Future
Interstate Highway System

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The National Academies of
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Preface

In Section 6021 of the Fixing America's Surface Transportation Act of 2015, the U.S. Congress asked the Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine to conduct a study of the actions needed to upgrade and restore the Interstate Highway System to fulfill its role as a crucial national asset, serving the needs of people, cities and towns, businesses, and the military while remaining the safest highway network in the country. To conduct this study, TRB formed the Committee on the Future Interstate Highway System. The committee members were selected for their expertise in the areas of civil engineering (highway construction, maintenance, operations, and safety); transportation; public transportation; highway safety; systems engineering; environmental and community impact mitigation; modeling; funding and finance; supply chain and freight; and economics (biographical information on the committee members is provided in Appendix A).

Understanding the perspectives of providers, operators, and users of the Interstate System, as well as national experts and private-sector stakeholders, was vital to the study. To gain this understanding, the committee held eight public listening sessions across the nation, focused on learning from experts and gathering information on specific topics related to the Interstate System, as well as their views on needs and aspirations for the system's future. One additional national public session was held online via webcast.

To help conduct its analyses and deliberations, the committee also commissioned white papers exploring in depth five key topics that will influence the Interstate Highway System of the future: demographics and population, economics, technology, climate change, and projected travel demand. In addition, a consulting team, led by Cambridge Systematics and WSP USA Inc., conducted extensive computer modeling of a variety of scenarios relating to the future system.

This report reflects the contributions from all of these sources, together with information gleaned from the committee's review of the salient literature and the collective expertise of its members. Thus informed, the committee formulated a series of recommendations, characterized as a blueprint for action, designed to guide the reinvestment needed to meet the challenges of today and those anticipated for the future, thereby renewing and restoring a system that is critical to nearly every aspect of American life.

ACKNOWLEDGMENTS

The committee thanks the many individuals who contributed to its work on this study.

During its information-gathering sessions, which were open to the public, the committee was briefed by officials, topical experts, and Interstate users on a diverse range of subjects. The committee thanks the more than 100 such individuals who shared information and their views on the issues addressed by the study. Among them were the following federal and state executives who presented to the committee: James Bass, Executive Director, Texas Department of Transportation; Randall Blankenhorn, Secretary, Illinois Department of Transportation; Carlos Braceras, Director, Utah Department of Transportation, and President of American Association of State Highway and Transportation Officials (AASHTO); Bruce Busler, Director, Joint Process Analysis Center, and Executive Director for Transportation, U.S. Transportation Command, U.S. Department of Defense (DoD); Kristin French, Principal Deputy Assistant Secretary of Defense, and Acting Assistant Secretary, Logistics and Materiel Readiness, DoD; Gregory Nadeau, Federal Highway Administration (FHWA) Administrator (2015–2017); William Panos, Director and Chief Executive Officer, Wyoming Department of Transportation; Michael Trentacoste, Associate Administrator for Research, Development, and Technology (2009–2017); Walter "Butch" Waidelich, FHWA Executive Director (2016–2018); and Bud Wright, Executive Director of AASHTO.

The committee also wishes to thank Thomas D. Everett, FHWA Executive Director, who served as the principal contact between FHWA and the committee and coordinated information requests from the committee to offices within the U.S. Department of Transportation (U.S. DOT). In addition, the American Automobile Association (AAA) provided archived maps dating to 1955, and the Insurance Institute for Highway Safety (IIHS) shared data regarding Interstate safety.

A number of other individuals also shared their expertise with the committee through five commissioned papers. Guangqing Chi, Pennsylvania State University, authored a paper on how a changing U.S. population and its evolving spatial patterns could affect demand for Interstate highways in various parts of the country. Mark Sieber and Glen Weisbrod, EDR Group, co-authored a second paper on how future highway demand will be affected by evolving shifts in the economy. Steven E. Polzin, University of South Florida, provided a paper on Interstate travel demand, its influence factors, and projections for the future. Steven E. Shladover, University of California, Berkeley, addressed how the development and deployment of connected and automated vehicle technology could affect the supply of and demand for transportation on the Interstates. And finally, Donald J. Wuebbles, University of Illinois, and Jennifer M. Jacobs, University of New Hampshire, examined climate change and how it could impact the condition and performance of the Interstate System.

Monica A. Starnes managed the study under the guidance of the committee and the supervision of Thomas R. Menzies, Jr., Director, Consensus and Advisory Studies, TRB. Together with Steven R. Godwin, they also drafted the report under the guidance of the committee. Rona Briere edited the report and Alisa S. Decatur prepared the report for prepublication. TRB staff Micah Himmel, Anusha Jayasinghe, and Katherine Kortum provided support for the study. Additionally, the staff and the committee thank Stephanie Seki, Fellow of the National Academies of Sciences, Engineering, and Medicine's Christine Mirzayan Science and Technology Policy Graduate Program, who contributed to the committee's research on the historical perspetive of the Interstate Highway System.

The committee's work was also supported by a consulting team led by Susan Binder, Jag Mallela, and Richard Margiotta, who conducted case studies and modeling and collected information under the committee's guidance. Alan Pisarski and Gary Maring, additional members of the consulting team, were instrumental in providing information to the committee.

The staff and committee thank Tom Boast, José Manuel Vassallo Magro, and Remy Cohen for input into and review of the international funding and financing material in Appendix J, as well as Adrian Moore for input into and review of material regarding mileage-based user fees. The committee also thanks Richard Arnold, Omar Smadi, and Martin Wachs for their interim review of the modeling approach.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The committee thanks the following individuals for their review of this report: Tom Adler, RSG; Richard Arnold, Oregon Department of Transportation; John W. Fisher (NAE), Lehigh University (Emeritus); Emil H. Frankel, Eno Center for Transportation; James L. Kirtley (NAE), Massachusetts Institute of Technology; Susan Martinovich, CH2M Hill; Carl L. Monismith (NAE), University of California, Berkeley (Emeritus); Ariel Pakes (NAS), Harvard University; Ananth Prasad, Florida Transportation Builders Association; Joseph L. Schofer, Northwestern University; Kumares C. Sinha (NAE), Purdue University; and Martin Wachs, University of California, Los Angeles.

Although the reviewers listed above provided many constructive comments, they were not asked to endorse the committee's conclusions and recommendations, nor did they see the final version of the report before its release. The review of the report was overseen by National Academy of Sciences members Charles F. Manski, Northwestern University, and Susan Hanson, Clark University. They were responsible for making certain that an independent review of the report was conducted in accordance with institutional procedures and that all review comments were carefully considered by the committee. Responsibility for the final content of the report rests solely with the authoring committee and the institution. Karen Febey, Senior Report Review Officer, TRB, managed the report review process.

Contents

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Acronyms and Abbreviations

AAA	American Automobile Association
AADT	annual average daily traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AET	all-electronic tolling
AMPO	Association of Metropolitan Planning Organizations
ATA	American Trucking Associations
ATM	active traffic management
ATRI	American Transportation Research Institute
Auto-ISAC	Automotive Information Sharing and Analysis Center
BCR	benefit-cost ratio
BEV	battery-electric vehicle
BPR	Bureau of Public Roads
BTS	Bureau of Transportation Statistics
C&P	*Conditions and Performance*
CAFE	corporate average fuel economy
CAV	connected and automated vehicle
CBD	Central Business District
CBO	Congressional Budget Office
CO	carbon monoxide
CO_2	carbon dioxide
CRCP	continuously reinforced concrete pavement

DDOT	District Department of Transportation
DoD	Department of Defense
DOT	Department of Transportation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EU	European Union
EV	electric vehicle
FAST Act	Fixing America's Surface Transportation Act
FDIC	Federal Deposit Insurance Corporation
FHWA	Federal Highway Administration
FRED	Federal Reserve Bank of St. Louis
GAO	U.S. Government Accountability Office
GDP	gross domestic product
GHG	greenhouse gas
GMSL	global mean sea level
GPS	Global Positioning System
GVW	gross vehicle weight
HERS	Highway Economic Requirements System
HLDI	Highway Loss Data Institute
HPMS	Highway Performance Monitoring System
HOT	high-occupancy toll (lane)
HOV	high-occupancy vehicle
HTF	Highway Trust Fund
HVUT	heavy vehicle use tax
IC	Interstate Construction
ICE	Interstate Cost Estimate
IRI	International Roughness Index
ITEP	Institute on Taxation and Economic Policy
MBUF	mileage-based user fee
MPO	metropolitan planning organization
NASA	National Aeronautics and Space Administration
NBI	National Bridge Inventory
NBIAS	National Bridge Investment Analysis System
NCHRP	National Cooperative Highway Research Program
NHCCI	National Highway Construction Cost Index

NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NMFN	National Multimodal Freight Network
NOAA	National Oceanic and Atmospheric Administration
NOx	nitrogen oxide
NRC	National Research Council
NYCEDC	New York City Economic Development Corporation
PHT	Pavement Health Track
PM_{10}	particulate matter
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SO_X	sulphur oxide
STRAHNET	Strategic Highway Network
TDF	travel demand forecasting
TRB	Transportation Research Board
TTI	Texas A&M Transportation Institute
U.S. DOT	U.S. Department of Transportation
VMT	vehicle-miles traveled
VOC	volatile organic compound
vphpl	vehicles per hour per lane
ZEV	zero-emission vehicle

Summary

The Interstate Highway System has conferred both broad and deep benefits on the nation. Not only does it connect and integrate the transcontinental United States, but it also has been pivotal for more than 50 years in shaping and supporting the country's demographic, spatial, economic, and social development. It functions as the main corridors for passenger and freight movement both within large urban agglomerations and between metropolitan and rural areas. It provides critical connections and services complementary to all of the country's other passenger and freight transportation networks and their nodes, including railroads, marine ports, airports, public transit, and local road systems. Because its impacts reverberate across the transportation sector, society, and the economy, it is imperative that the Interstate System not only be preserved and rehabilitated, but also renewed and modernized to adapt to the country's changing demographic, economic, climate, and technological landscape.

The Interstate Highway System's future is threatened by a persistent and growing backlog of physical and operational deficiencies and by a number of large and looming challenges. Most of its segments are decades old, subject to much heavier traffic than anticipated, and operating well beyond their design life without having undergone major upgrades or reconstruction. These aging and heavily used segments, whose ranks will grow over the next 20 years, are poorly positioned to accommodate even modest projections of future traffic growth, much less the magnitude of growth experienced since the system's inception in 1956.

As the nation moves further into the 21st century and as transformations in the vehicle fleet and vulnerabilities due to climate change place new demands on the country's transportation infrastructure, the prospect of an aging and worn Interstate Highway System that operates unreliably is concerning. Unless a commitment is made soon to remedying the system's deficiencies and to preparing it for the challenges that lie ahead, there is a very real risk that the system will become increasingly congested; far more costly to operate, maintain, and repair; less safe; incompatible with evolving technology; and vulnerable to the effects of a changing climate and extreme weather. The consequences from these deficiencies will spill over into all the passenger and freight modes that complement and connect to the system.

Congress called for the present study to inform pending and future federal investment and policy decisions concerning the Interstate Highway System. Specifically, Congress asked for recommendations on the actions necessary to restore and upgrade the system to meet the growing and shifting demands of the 21st century, through the next 50 years. The study's findings, summarized below, point to the need for a major reinvestment in the system. Collectively, they serve as a call for action—carried out not through a series of incremental steps to repair the current system but through a concerted and adequately funded national campaign of system renewal and modernization patterned after the visionary program that initially produced the Interstates.

LOOMING CHALLENGES

The committee identified major challenges confronting decision makers as they contemplate the future of the Interstate Highway System. These challenges include

- Commencing the enormous task of rebuilding the system's pavements, bridges, and other assets and their foundations before they become unserviceable and less safe;
- Meeting the growing demand for investments in physical capacity, especially on the urban portions of the system, and for more active and innovative management of this capacity in large metropolitan areas that continue to experience most of the country's population and economic growth;
- Ensuring that the system remains responsive to, and aligned with, continued changes in the geography and composition of the country's population and economy, and that its connections with the other modes of local, interregional, and long-distance transportation are maintained and strengthened;
- Continually improving system safety as traffic volumes increase, new highway and vehicle technologies are introduced, and the system is modified to increase capacity and throughput;

- Ensuring that the system is robust and adaptable to changing vehicle technologies, and avoiding premature investments in assets and the introduction of standards that would hinder or even foreclose useful development pathways;
- Adopting funding mechanisms that are equitable and efficient, do not unduly impose the burden of payment on future generations or on less financially equipped groups, and do not disadvantage or divert resources from other highways and modes of passenger and freight transportation; and
- Developing and implementing strategies for incorporating future climate conditions into infrastructure and operations planning, starting with the development of design and construction standards that assume greater frequency and severity of extreme weather events.

AN INVESTMENT IMPERATIVE

Because of the uncertainties associated with forecasting developments far into the future, specific uncertainties about the pace and form of motor vehicle automation, and the absence of appropriate modeling tools and data, the committee restricted its time horizon to the next 20 years for estimating system investment needs. During this period, the transition to vehicle automation is expected to remain at an early stage and have limited effects on Interstate travel. Investment needs over the 20-year horizon are likely to be dominated by a necessity to rehabilitate and reconstruct large portions of the Interstate System, which can be more confidently predicted than needs arising from changes in system use.

Most of the Interstate Highway System has far exceeded its design life or will do so over the next 20 years. Only limited planning and budgetary preparations have been made to fix the deterioration that has already occurred and to prevent the physical and operational deficiencies that will ensue. Recent combined state and federal capital spending on the Interstates has been on the order of $20–$25 billion annually (see Figure S-1). The information gathering, modeling, and case studies that informed this study indicate that this level of spending is too low—by at least 50 percent—just to proceed with the long-deferred rebuilding of the system's aging and deteriorating pavements and bridges. The committee estimates that investments averaging more than $30 billion per year will be needed over the next 20 years to repair and reconstruct these assets from damage already done and that is forthcoming from the effects of age and further use. Figure S-1 shows how these rehabilitation and reconstruction investment needs do not change much across different scenarios of growth in vehicle miles traveled.

Along with these substantial investments in pavement and bridge rehabilitation and reconstruction, additional investments will be required to

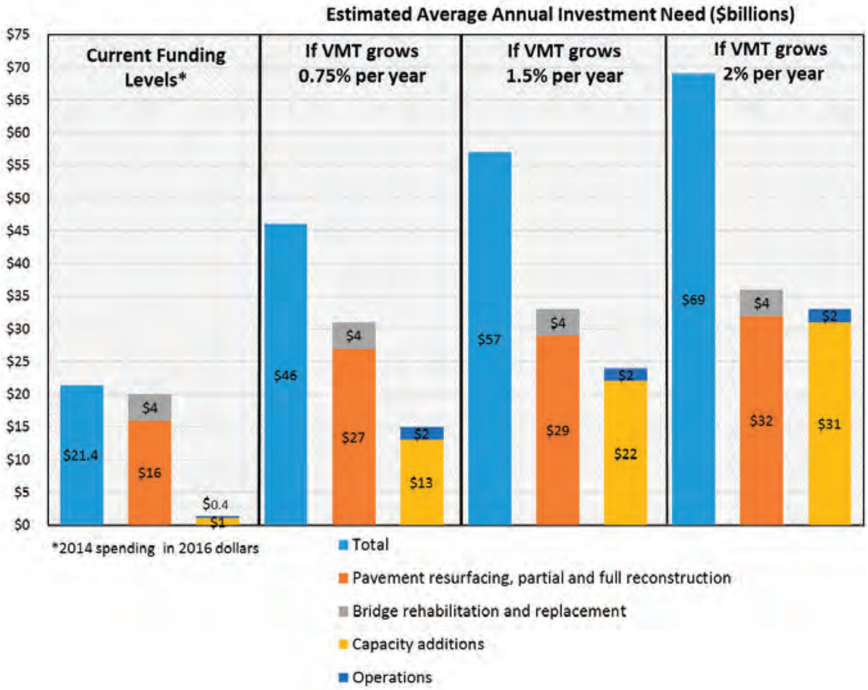

FIGURE S-1 Estimated spending needs for Interstate highway renewal and modernization over the next 20 years.

NOTES: All dollar figures are converted 2016 values. The most recent complete data on Interstate highway spending is for 2014. See Chapter 5 for details on computation methods. VMT = vehicle-miles traveled.

expand and manage the Interstate Highway System's capacity to handle future traffic. Investments that will be required to accommodate this traffic demand are much more difficult to project. Significant capacity additions will likely be required because of growth of urban areas that are not well connected to the Interstate System and because of the continued growth of large metropolitan regions. However, the size, location, and timing of these needed additions will depend on a host of factors related to changes in the population and economy, how travelers respond to congestion and the supply of new capacity, whether new capacity is restricted to specific users, and the availability of options other than Interstate travel. Transportation agencies, especially in urban areas, may substitute more active operations and demand management measures, such as congestion tolling, for spending on lane widening and other physical additions to Interstate highways, particularly where the acquisition of additional right of way is very expensive or unacceptable to local communities. Although connected and automated vehicles are likely to have limited effects on travel demand in the nearer term, expectations about their longer-term impact may influence transportation agency decisions about whether and where to invest in Interstate capacity, especially in 10 to 15 years.

In addition to the many uncertainties and interdependencies noted above, the committee found that the available data and models do not have the capability to predict the effects of changes in capacity on travel demand across broad portions of the Interstate network. By stretching the national-level modeling capabilities that do exist and using a range of historically informed rates of growth in future Interstate travel, the committee could, at best, make rough approximations of the magnitude of spending that might be needed for physical and operational capacity improvements over the next 20 years. The models calculate that if travel on the system is assumed to grow at a modest pace comparable to the forecast U.S. population (0.75 percent growth annually), transportation agencies will need to invest an average of $15 billion per year for such improvements. These investments would need to be considerably larger, by about 50 to 100 percent, if travel on the system is assumed to grow at a pace closer to recent historical averages (see Figure S-1).

Thus, an approximation of the total state and federal spending that will be needed to renew and modernize the Interstates over the next 20 years averages $45–70 billion per year. The figures in this range are 2 to 3 times higher than current spending levels, and even 50 percent higher when only considering the outlays that will be required for the pavement and bridge upgrades that can be projected with higher confidence. However, even these estimated investment levels may be inadequate. Because of the lack of analytical tools and adequate databases, they do not include the funding required to reconfigure and reconstruct many of the Interstate System's roughly 15,000 interchanges, nor do they include the resources needed to make the system more resilient to the effects of climate change, add special-purpose and managed lanes that can allocate system capacity more efficiently in and around metropolitan areas, and "rightsize" the system's scope of coverage through network extensions and in some cases replacement and modification of controversial urban segments. While these investment needs could not be estimated even roughly for this study, they are certain to require billions, and perhaps tens of billions, in additional annual spending.

RECOMMENDATIONS

The original Interstate Highway Construction Program was underpinned by a long-term, collaborative commitment among the states and the federal government. A comparable partnership is needed to renew and modernize the system and to ensure that it is resilient and responsive to the changing demands of users. Central to that partnership is federal leadership and a resolve to restore the Interstate Highway System's premier status and ensure that this status is no longer allowed to obsolesce. The recommendations that follow provide a blueprint for Congress to act on that resolve.

Congress should legislate an Interstate Highway System Renewal and Modernization Program (RAMP). This program, presumed to be pursued without sacrificing normal ongoing system maintenance and repair, should focus on reconstructing deteriorated pavements, including their foundations, and bridge infrastructure; adding physical capacity and operations and demand management capabilities (e.g., tolling) where needed; and increasing the system's resilience. RAMP should be modeled after the original Interstate Highway System Construction Program by

- Reinforcing the traditional program partnership in which the federal government provides leadership in establishing the national vision for the overall system, the bulk of the needed funding, and overall standards, while states prioritize and execute projects in their continued role as owners, builders, operators, and maintainers of the system;
- Ensuring that the federal share of project spending is comparable to the 90 percent share of the original Interstate Highway System Construction Program;
- Committing the federal government to supporting projects from start to finish, but with a cap on total federal funding (i.e., a cost-to-complete approach); and
- Developing transition plans for updating and incorporating standards for system uniformity and safety to accommodate changing vehicle and highway technologies, environmental and climate conditions, and usage patterns.

Congress should, as a near-term step, (1) increase the federal motor fuel tax to a level commensurate with the federal share of the required RAMP investment, and (2) adjust the tax as needed to account for inflation and changes in vehicle fuel economy.

To ensure that the federal government's long-term commitment to RAMP is not threatened by declining fuel tax revenues as the vehicle fleet and its energy sources evolve, **Congress should prepare for the need to employ new federal and state funding mechanisms, such as the imposition of tolls or per-mile charges on users of the Interstate Highway System.**

To provide states and metropolitan areas with more options for raising revenue for their share of RAMP investments and for managing the traffic demand on and operations of Interstate segments that offer limited opportunity for physical expansion, **Congress should lift the ban on tolling of existing general-purpose Interstate highways.** As a condition for imposing those tolls, states should be required to assess their impact on current users and offer alternative mobility options for those users significantly and disproportionately harmed by the tolls.

A "rightsizing" component of RAMP should address current and emerging demands to extend the Interstate System's length and scope of coverage, and to remediate economic, social, and environmental disruptions caused by highway segments that communities find overly intrusive and are not deemed vital to network and intermodal traffic. **Congress should direct the U.S. Department of Transportation and the Federal Highway Administration to develop criteria for such system rightsizing using a consultative process that involves states, local jurisdictions, highway users, and the general public.** The criteria and their development should take into account the interest in ensuring

- Adequate system connectivity to accommodate network flows of Interstate travel and commerce, including traffic from other important passenger and freight transportation modes;
- System access to growing centers of population and economic activity;
- System resilience through redundancy or other means as appropriate; and
- Responsiveness to national defense needs.

CONCLUDING COMMENTS

Implementation of the above recommendations, together with the recommended complementary actions summarized in Box S-1, would represent a fundamental shift away from a federal policy that has lost focus on the Interstate System and the commitment to funding it adequately. These actions would restore the system's premier status within the nation's highway program in a manner that is aggressive and ambitious, although by no means novel. Taking these actions would rekindle a tried-and-true federal–state partnership; reinforce the system's long-standing reliance on user fees to provide a fair, adequate, and reliable source of funding; and reassert the forward-looking vision that was instrumental to the genesis of this crucial national asset more than a half-century ago. At that time, the nation's leaders endorsed a modern highway system that would confer large and lasting societal and economic benefits, a vision whose realization required a strong and continuing national commitment. Today, the nation is experiencing, and can anticipate, new expectations for the system's condition, performance, and use. Meeting those expectations will require the same forward-looking outlook and commitment that informed the system's creation—a rededication to that original vision that reshapes and reequips the system to serve generations to come.

BOX S-1
A Blueprint for Action

Recommendation 1. Congress should legislate an Interstate Highway System Renewal and Modernization Program (RAMP). This program, presumed to be pursued without sacrificing normal ongoing system maintenance and repair, should focus on reconstructing deteriorated pavements, including their foundations, and bridge infrastructure; adding physical capacity and traffic demand and operations management capabilities where needed; and increasing the system's resilience.

Recommendation 2. A "rightsizing" component of RAMP should address current and emerging demands to extend the Interstate System's length and scope of coverage, and to remediate economic, social, and environmental disruption caused by highway segments that communities find overly intrusive and are not deemed vital to network and intermodal traffic. Congress should direct the U.S. Department of Transportation (U.S. DOT) and the Federal Highway Administration (FHWA) to develop criteria for such system rightsizing using a consultative process that involves states, local jurisdictions, highway users, and the general public.

Recommendation 3. To better ascertain the spending levels required for RAMP investments, Congress should direct U.S. DOT and FHWA to join with the states to assess the foundational integrity of the system's pavements and bridges, and identify where full reconstruction is needed based on accepted life-cycle cost principles.

Recommendation 4. To pay for RAMP investments, Congress should, as a near-term step, (1) increase the federal motor fuel tax as needed to a level commensurate with the federal share of the required investment, and (2) adjust the tax as needed to account for inflation and changes in vehicle fuel economy.

Recommendations 5. To provide states and metropolitan areas with more options for raising revenue for their share of RAMP investments and for managing the operations of Interstate segments that offer limited opportunity for physical expansion, Congress should lift the ban on tolling of existing general-purpose Interstate highways. As a condition for imposing those tolls, states should be required to assess their impact on current users and offer alternative mobility options for those users significantly and disproportionately harmed by the tolls.

Recommendations 6. To ensure that the federal government's long-term commitment to RAMP is not threatened by declining fuel tax revenues as the vehicle fleet and its energy sources evolve, Congress should prepare for the need to employ new federal and state funding mechanisms, such as the imposition of tolls or per-mile charges on users of the Interstate Highway System.

Recommendation 7. To support renewal and modernization investment decisions, Congress should direct, and provide sufficient funding for, U.S. DOT and FHWA to develop modeling tools and databases that track the full condition of Interstate assets, including interchanges, and their reconstruction history; can be used to assess transportation options that can supplement or substitute for additions to Interstate highway capacity; allow for the monitoring and modeling of network-level traffic flows on the Interstate Highway System; and further federal and state understanding of the demand for long-distance and interregional passenger and freight travel by highway and other modes. Because these recommended activities are important for guiding reinvestment in the Interstate System, careful consideration should be given to carrying them out in an effective and efficient manner.

Recommendation 8. Congress should direct U.S. DOT and FHWA, working with states, industry, and independent technical experts, to start planning the transition to more automated and connected vehicle operations. This effort should entail performing the needed research and updates to Interstate Highway System requirements and standards so as to ensure that basic intelligent transportation system (ITS) instrumentation is adopted on a consistent and system-wide basis, and that the uniformity and other attributes of pavement markings, interchange design, and the like are capable of facilitating eventual Interstate use by connected and automated vehicles. An emphasis should be placed on ensuring that renewal and modernization projects give full consideration to safety impacts, including the deployment of advanced design and operational features that have demonstrated effectiveness in improving safety, and that cybersecurity protections are incorporated into the designs and upgrades of the Interstate highways and the vehicles that use them.

Recommendation 9. Expanding on earlier legislative directives (e.g., the Moving Ahead for Progress in the 21st Century [MAP-21] Act and the Fixing America's Surface Transportation [FAST] Act) for transportation agencies to consider resilience in long-term planning, Congress should direct U.S. DOT and FHWA to substantiate that state Interstate highway renewal and modernization projects have fully taken into account the need for resilience. To support these efforts, U.S. DOT and FHWA should be directed to assess the vulnerability of the Interstate Highway System to the effects of climate change and extreme weather; develop standards, in conjunction with states, for incorporating cost-effective resilience enhancements into projects; and develop and maintain a database of cost-effective practices and resilience strategies employed by state highway and other transportation agencies, including any funding mechanisms dedicated to support resilience planning and implementation.

Recommendation 10. Congress should direct U.S. DOT and FHWA to ascertain the Interstate Highway System's contribution to the country's emission of greenhouse gases and recommend options for reducing this contribution in conjunction with reductions in other emissions of pollutants. The effort should build on past initiatives, such as legislation requiring states to consider the emissions impacts of capacity expansion and demand-management options, and legislation mandating a federal program to examine the siting of facilities that support alternative-fueled vehicles, such as electric vehicle charging stations located on Interstate highway corridors.

1

Introduction

The Interstate Highway System is not only a testament to America's engineering prowess but also an embodiment of what the country can accomplish when its leaders are united behind a common vision. It is perhaps not surprising that the generation that waged World War II would conceive of, plan, and build the Interstates. The president who led the country's war effort—Franklin D. Roosevelt (see Figure 1-1)—sketched the trunk Interstate routes on a map of the continental United States (Edwards 2018). One of his top generals during the war—Dwight D. Eisenhower (see Figure 1-1)—would later sign into law a dedicated fuel tax as the means to pay for the system's construction. The soldiers and sailors who returned from the war would have a lead role in designing, engineering, building, and administering this nascent system.

Before President Eisenhower signed the Federal-Aid Highway Act of 1956, which authorized and created a funding mechanism for the Dwight D. Eisenhower National System of Interstate and Defense Highways, the country's interstate and interregional highway network consisted of a loosely integrated collection of state and U.S. routes. While it included some modern freeways with divided lanes and access control, often on tolled turnpikes, the collection lacked the interconnectivity and standardized design that would set the new Interstate Highway System apart. At the dawn of the Interstate System, long-distance travel often meant driving on routes interrupted by traffic lights; passing through town centers; and traversing roads of widely varying quality, signage, and configuration (TRB 2016, 45). Even shorter trips between neighboring cities could be slow and meandering. Today, the

FIGURE 1-1 President Franklin Roosevelt and General Dwight Eisenhower in 1943.
SOURCE: National Archives.

ability to drive hundreds of miles on the same route through multiple states without crossing a single intersection is taken for granted.

In the transportation domain, the United States has arguably never accomplished more than it did during the Interstate era. The system has become vital to the nation's economy and central to the daily lives of many millions of Americans. Today, it accounts for one-quarter of the country's vehicle-miles traveled (VMT), including more than half of all long-haul truck VMT—even though it accounts for just slightly more than 1 percent of public road mileage (FHWA 2017a). With a layout that closely resembles the network envisioned by Presidents Roosevelt and Eisenhower, the system serves more traffic—more than 800 billion VMT annually (FHWA 2017b)—than was traveled on the entire U.S. road network in 1956 when the Interstate System was launched (FHWA 2014).

Much of the Interstate System, however, is now more than 50 years old and is showing its age from the stress of heavy and largely unanticipated levels of use. While the system's scope of coverage, or route footprint, has largely remained the same throughout this period, the U.S. population and economy have undergone major changes, including marked growth in parts of the country that were lightly populated in 1956. Such locales retain a density of Interstate routes today that is modest relative to their current and forecast populations. Originally designed to serve cities by connecting them to one another, the urban portions of the system have transformed metropolitan regions by becoming primary corridors for commuting and other local travel, accommodating traffic volumes not imagined when the routes were initially planned.

As the owners and operators of the Interstate Highway System, states have regularly undertaken its maintenance and repair and periodically reconstructed portions of the system. Nonetheless, they have been severely challenged to keep the system's assets in satisfactory condition and its operations and capacity aligned with the growth and changes in traffic demand. Original traffic projections by many states and metropolitan regions grossly underestimated the popularity of the Interstate System not only for local commuting but also for the transport of freight. Increasingly heavier trucks using the system in higher volumes have added to the system's punishment and have led to a mismatch between the conditions for which the highways were designed and the conditions they have faced. On many highway segments, pavement bases and subbases date back to the original Interstate construction phase or before, necessitating more frequent—and often complex and costly—maintenance and repair work on heavily trafficked, high-demand routes. Moreover, while many bridges in southern and western states have thus far remained serviceable beyond their 50-year design lives without major repair work, many bridges in northern and midwestern states that have sustained severe weather and high traffic loadings have required frequent redecking. Aging bridges across the system, including a growing share that have exceeded their design lives, will require major repair, rehabilitation, and replacement, an inevitability that cannot be forestalled much longer.

Fortunately, as it enters its seventh decade of service, the Interstate System is reaping, or set to reap, the benefits of dramatic, unforeseen technological changes. Advances in materials, construction methods, electronics, communications, and other areas are providing new capabilities and opportunities to increase and manage traffic capacity; reduce system congestion and environmental impacts; increase system safety; and reduce the cost of highway maintenance, repair, and reconstruction. However, owners of the system are also facing other unforeseen developments, notably the need to reduce the system's vulnerability and increase its resilience to the effects of climate change. And as highly instrumented vehicles and highways become commonplace, a new challenge will be confronted in the field of cybersecurity.

In the context of the historical pattern of underestimating traffic loadings, together with the unanticipated requirements for the system to be made resilient to future climate change and capable of accommodating an increasingly automated vehicle fleet with concomitant cyber threats, the Interstate Highway System and its upkeep must be viewed through the lens of an ever-changing demographic, economic, environmental, and technological landscape. To keep pace with these changes, the system cannot simply be preserved and restored; rather, planning and reinvestment choices must be made with an emphasis on renewal, modernization, and adaptability. The latter emphasis is particularly critical because the expected useful life of most highway elements far exceeds the ability to foresee the relatively distant future (say, beyond 20 years).

STUDY CHARGE

In December 2015, the Fixing America's Surface Transportation (FAST) Act was signed into law. Section 6021 of the law provides for the National Academies of Sciences, Engineering, and Medicine, under the auspices of the Transportation Research Board (TRB), to "conduct a study on the actions needed to upgrade and restore the Dwight D. Eisenhower National System of Interstate and Defense Highways to its role as a premier system that meets the growing and shifting demands of the 21st century." The full study charge, as it appears in the law, is shown in Box 1-1; also shown is an additional task requested by the Federal Highway Administration (FHWA), which provided funding for the study. In essence, TRB was asked to convene a special study committee to consider

- Future demands on the Interstate Highway System, including commercial and passenger traffic flows to serve future economic activity and growth;
- The expected condition of the system over the next 50 years, including long-term deterioration and reconstruction needs;
- Technological capabilities that will enable the application of modern standards of construction, maintenance, and operations and the furthering of safety and system management;
- Highway routes that should be added to the system to serve national traffic flows more efficiently;
- The resources necessary to restore and upgrade the system to meet the growing and shifting demands of the 21st century; and
- How the system can provide more access to such opportunities as employment and education, and have positive impacts on communities and quality of life.

In the FAST Act, Congress encouraged the study committee to consult with FHWA and state departments of transportation (DOTs), metropolitan and local transportation planning agencies, the motor carrier and freight shipping industries; other operators and users of Interstate highways; highway safety advocates; and other interests, as deemed appropriate by the committee.

The committee was further advised to employ and build on the methodology for estimating Interstate investment needs proposed in the report of National Cooperative Highway Research Program (NCHRP) Project 20-24(79), *Specifications for a National Study of the Future 3R, 4R, and Capacity Needs of the Interstate System* (Miller et al. 2013). This methodology, which is discussed in greater detail later in the present and subsequent chapters of this report, involves the application of FHWA's long-standing modeling systems for highway and bridge investment needs, coupled with case studies of Interstate construction and reconstruction projects. As described in the NCHRP report, the purpose of the methodology is to relate current Interstate System condition and performance levels to future levels that will be necessitated by changes in system use, and to estimate the investments required to achieve the needed condition and performance levels.

Drawing on its members' experience and expertise, informed by consultations with outside parties and methods for estimating investment needs, the study committee was asked by Congress to make recommendations "regarding the features, standards, capacity needs, application of technologies, and intergovernmental roles to upgrade the Interstate System." The committee was further asked to indicate any revisions to law that may be needed to further any recommended actions, as well as to identify the required resources.

STUDY APPROACH

As detailed in Box 1-1, the multifaceted charge for this study delineates a series of issues to be addressed (e.g., future demands on the system and levels of investment needed to meet those demands), offers instructions and advice on the conduct of the study (e.g., consulting with outside parties and using particular methodologies for estimating investment needs), and identifies candidate topics for recommended action (e.g., system features, standards, capacity needs, application of technologies, intergovernmental roles). The charge is also clear in inviting the study committee to advise on any changes in law that may be needed to further the recommended actions—presumably to include any changes that may be needed to authorize and appropriate future investments in the Interstate Highway System.

To fulfill this charge, the National Academies appointed a committee whose members brought to bear a wide and varied range of perspectives,

BOX 1-1
Section 6021 FAST ACT, Request for This Study

The Secretary shall enter into an agreement with the Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine to conduct a study on the actions needed to upgrade and restore the Dwight D. Eisenhower National System of Interstate and Defense Highways to its role as a premier system that meets the growing and shifting demands of the 21st century.

In conducting the study, the Transportation Research Board shall build on the methodologies examined and recommended in the report prepared for the American Association of State Highway and Transportation Officials titled *National Cooperative Highway Research Program Project 20-24(79): Specifications for a National Study of the Future 3R, 4R, and Capacity Needs of the Interstate System,* dated December 2013.

The study—(1) shall include specific recommendations regarding the features, standards, capacity needs, application of technologies, and intergovernmental roles to upgrade the Interstate System, including any revisions to law (including regulations) that the Transportation Research Board determines appropriate; and (2) is encouraged to build on the institutional knowledge in the highway industry in applying the techniques involved in implementing the study.

In carrying out the study, the Transportation Research Board shall determine the need for reconstruction and improvement of the Interstate System by considering—(1) future demands on transportation infrastructure determined for national planning purposes, including commercial and private traffic flows to serve future economic activity and growth; (2) the expected condition of the current Interstate System over the period of 50 years beginning on the date of enactment of this Act, including long-term deterioration and reconstruction needs; (3) features that would take advantage of technological capabilities to address modern standards of construction, maintenance, and operations, for purposes of safety, and system management, taking into further consideration system performance and cost; (4) those National Highway System routes that should be added to the existing Interstate System to more efficiently serve national traffic flows; and (5) the resources necessary to maintain and improve the Interstate System, including the resources required to upgrade the National Highway System routes identified in paragraph (4) to Interstate standards.

In carrying out the study, the Transportation Research Board—(1) shall convene and consult with a panel of national experts, including operators and users of the Interstate System and private-sector stakeholders; and (2) is encouraged to consult with—(A) the Federal Highway Administration; (B) states; (C) planning agencies at the metropolitan, state, and regional levels; (D) the motor carrier industry; (E) freight shippers; (F) highway safety groups; and (G) other appropriate entities.

Additional Task Requested by the Federal Highway Administration

The study will also consider the role the Interstate System, and modifications to it, can play in providing accessibility for Americans to opportunities such as employment and education and the impact transportation decisions can have on communities and quality of life. These considerations will be examined through case studies and, where quantifiable and appropriate, will be incorporated into cost estimates for reconstructing and expanding the Interstate System.

experience, and expertise in highway and transportation system planning; construction, operations, and administration; civil and environmental systems and transportation engineering; economics; law and public policy; traffic safety; and travel and demand modeling (see Appendix A for biographical sketches of the committee members).

The committee was immediately occupied by determining how to conduct a study whose charge entails an examination of such a diverse set of issues, presumes at least some insight into the future, advises on methods to be used for information gathering and analysis, and entrusts the committee with making recommendations on needed changes in law and system resources. The committee conducted several meetings in which it analyzed the study charge and made choices about how best to fulfill it. This task entailed gathering and assessing information and pursuing various avenues of inquiry and analysis, some which proved more fruitful than others.

The following sections explain the approach ultimately taken, including the reasons for bounding the study scope and employing certain methods of analysis. The final section of this chapter describes how the report is structured to present the study results.

Decisions on the Study Scope

Asked to consider future demands on the Interstate System and its expected performance and condition over the next 50 years, the committee had to decide how best to represent the further-out decades of this period, as well as the system's broader and potentially evolving role as it connects to and interacts with other highways and transportation modes to move people and goods locally, regionally, nationally, and internationally. The committee recognized that by expanding the study scope in these temporal and spatial directions, it would face significant descriptive and analytic challenges in attempting to account for the many variables and interdependencies arising over long time horizons and across a system whose individual segments and routes have many context- and location-specific functions. The committee decided that, because of these challenges and in light of the paucity of data and modeling capabilities to meet them, it should focus the study on the next two decades when approximating investment needs for the Interstate System, while acknowledging the impracticality of accounting for the many ramifications of these investment choices as they reverberate across other highways and transportation modes. The rationale for these decisions is explained below.

Time Frame of Investment Needs Analysis

Because the Interstate Highway System consists of many long-lived assets, all decisions about capital investment in the system are by implication long-range in nature. Estimating investment needs for the entire Interstate System 50 years into the future, however, would require numerous assumptions, and much speculation, about many prospective developments and their interactions. The committee concluded that such long-range forecasting would yield a wide-ranging, low-confidence set of investment needs estimates having limited value for decision making. It decided instead to narrow its time horizon for estimating these needs to the next 20 years.

A number of future uncertainties contributed to this scoping decision, from the country's changing population size, composition, and spatial distribution to the nature and pace of technological change, including the prospective development of increasingly automated and connected vehicles and their potential to affect highway demand and supply. The committee also lacked the data and modeling capabilities needed to test a large number of potential future scenarios. Because the modeling systems available for estimating highway investment needs are designed to inform Congress about near-term (~5 years) spending levels, they depend on baseline information about the condition and performance of the existing highway system. As time passes, one would expect this baseline to become less representative of future conditions. Experience shows that over the longer term, and especially over a period of decades, changes in the condition and supply of highways and other transportation modes can have large effects on the level and pattern of travel demand. The Interstate System itself is a testament to this impact, widely credited with spurring the country's economic development and expanding metropolitan areas over the past 60 years to affect where, how often, and how far people drive and use other transportation modes.

Having little choice but to use available models to estimate future investment needs for the Interstate System, the committee was reluctant to apply them to a period beyond 20 years, when the cumulative effect of these demand and supply interactions is likely to be substantial. A 20-year time frame also involves a great deal of uncertainty for modeling, particularly for estimating capacity-related investment needs that will depend on future levels of travel on the Interstate System. Significant capacity additions will likely be required over this period because of growth of urban areas that are not well connected to the Interstate System and because of the continued growth of large metropolitan regions. The size, location, and timing of these needed additions will depend on a host of factors related to changes in the population and economy, how travelers respond to congestion and the supply of new capacity, and the availability of options other than Interstate travel.

Yet, the system's future over the next 20 years is not imponderable. Over this period, the system can reasonably be expected to experience increasing demand in line with a growing population and economy, with much of this demand taking place on urban segments of the Interstate

System that are already heavily used and projected to account for most of the country's population growth. Although increasingly automated and connected vehicles may be entering the fleet, their impacts on travel demand should be marginal over most of the time frame. By stretching the national-level modeling capabilities that exist and using a range of travel growth rates indicative of recent travel behavior, the committee concluded that it could at least make rough approximations of the magnitude of spending that might be needed for capacity-related improvements over the next 20 years. Moreover, during this period, the cost of repairing and reconstructing Interstate assets that have already incurred significant deterioration from the effects of age and past use will be coming due, and these costs can be modeled with greater confidence.

Relationship of Interstates to Other Highways and Modes

The Interstate Highway System accounts for about 25 percent of all VMT nationwide in the country, and an even larger share of travel for longer-distance movements of high-value freight. The urban portions of the system have become commuter corridors that have shaped the pattern of metropolitan land development and the use and configuration of other local and regional transportation systems, such as public transit. Interstates connect the country's nearly 400 metropolitan areas, and in many cases are the only available means of transportation for intercity and interregional trips between neighboring metropolitan areas 50 to 200 miles apart (TRB 2016). By connecting with airline, marine, and rail terminals, the Interstates are a vital part of the country's intermodal freight system, sometimes used for moving traffic short distances to and from these terminals and at others times for longer-haul movements to and from them. Depending on the location and purpose of travel, the Interstates connect to, compete with, and complement other highways and transportation modes from public transit and airline service to passenger and freight rail.

Full and accurate depictions and analyses of the role of the Interstate Highway System would account for its many functions across the passenger and freight transportation domains and at the local, interregional, and longer-distance levels. They would also take into account how these functions differ by specific location—for instance, depending on the availability of substitute and complementary modes (e.g., passenger rail for intercity travel and urban rail for commuter service)—and by specific transportation purpose, for instance, depending on the time-sensitive nature of passenger trips and freight movements. Such an accounting of the Interstate System's role within the broader transportation system, including its impact on other highways and their use, would be far more revealing about system investment needs and impacts than analyses focused on the system as if it functioned alone. The committee recognizes the desirability of assuming such a broad and comprehensive perspective on the Interstate Highway System, but could think of no practical way to do so for the purpose of estimating investments needs and their impacts.

As is the case for estimating longer-range investment needs, neither the data nor the modeling capabilities required to allow for rich depictions and analyses of the Interstate Highway System's role within the broader transportation system exist at the national level. For example, the only national-level database on longer-distance passenger travel that includes highway trips is the American Travel Survey, which was last updated more than 20 years ago. Inasmuch as the Interstate highways are the main conduits for long-distance travel, this data gap, which has been documented in other reports (TRB 2011, 2016), limits understanding of the Interstate System's functionality and interconnectivity with other modes. While some states and metropolitan planning organizations have travel survey data and models that disaggregate travel by activity (e.g., commuting versus shopping), the state- and metropolitan-specific nature of these data and models do not lend themselves to extrapolation over the entire Interstate System for the purpose of estimating system-level investment needs.

While reflecting these practical reasons for limiting the scope of this study to the Interstate Highway System when estimating investment needs, this report does not lose sight of the system's impacts on the rest of the country's transportation system and its elements. In considering its recommendations, for instance, the committee was cognizant of this wider impact on matters ranging from how investments in the Interstate System are funded so as not to disadvantage or draw resources from other modes to concerns about how a congested and physically deteriorating Interstate System could adversely affect the intermodal freight system.

Methods of Analysis

Outside Consultations

Asked to seek input from outside experts and parties, and recognizing the importance and value of such consultation, the committee scheduled a number of public sessions—both in conjunction with full committee meetings and as part of subcommittee meetings held in locations across the country. Speakers were invited to provide information and their views on the issues included in the study charge. Participants in these sessions included but were not limited to

- Officials from FHWA and state transportation agencies and metropolitan planning organizations, as well as federal, state, regional, and local authorities having related responsibilities;

- Representatives of urban transit systems, the trucking and shipping sectors, and the automobile industry;
- Experts in public policy, economics, and engineering and those with prior highway transportation experience;
- Experts in the technology of highway construction, vehicles, energy, telecommunications, and other relevant fields and industries;
- Practitioners of travel demand modeling and forecasting;
- Individuals and organizations advocating for energy conservation, community and environmental interests, and traffic safety; and
- Experts in transportation infrastructure funding and financing and the role of transportation in supporting national security logistics.

The more than 100 individuals who met with the committee are listed in Appendix B. Included among them were officials from 16 state DOTs; 5 other public transportation agencies; 4 federal agencies; 5 corridor coalitions; 6 metropolitan, regional, or civic planning organizations; 2 city governments; 1 tribal transportation committee; 16 private-sector companies; 14 industry associations and nonprofit organizations; and 17 think tanks and universities. In addition, time was allocated at public meetings for comments by members of the general public.

The extent of interest in the study from such a wide range of parties reflects the Interstate System's social and economic importance. Furthermore, these consultations gave the committee a deeper appreciation of the impact and importance of the Interstate System to the economy and the daily lives of Americans.

These outside consultations reinforced the committee's initial concern that certain aspects of the study charge would be difficult to address in a direct and meaningful way. For instance, after meeting with experts in highway and vehicle technologies, the committee concluded that it would be unwise, or even impossible, to pursue an in-depth examination of the potential for technology to bring about new capabilities that would enable the application of new standards of construction, maintenance, and operations and safety over the entire 50-year period of interest to the study. In examining the feasibility of performing such an examination, the committee acknowledged that technological progress will indeed lead to new and improved capabilities affecting each of these matters, and that these developments will temper some of the challenges that lie ahead in readying the Interstate Highway System for the future. In the past 20 years alone, there has been a revolution in intelligent transportation systems, highway materials such as ultra-high-performance concrete and corrosion-resistant steel reinforcement, and construction methods such as accelerated bridge construction. At the same time, however, predicting specific technological developments in the more distant future appeared to be a far-ranging and potentially speculative exercise that the committee could not envision yielding a productive outcome.

Similarly, even after hearing from many presenters about the importance of the Interstate Highway System to the economy and the daily lives of Americans, the committee could think of no good way to respond in a direct manner to the call for an examination of the system's future impact on access to employment and education or on communities and quality of life. The Interstate System is multipurpose, operates on a number of spatial scales, and serves a broad array of users, including commuters, shoppers, and commercial-service trucks traveling locally; people making leisure and business trips from one region to another; and long-haul freight trucks carrying a wide range of goods. In each case, the Interstates are part of a larger network of highways and transportation modes, some that are complementary and others that are substitutes, depending on the nature and purpose of the trip. In light of the Interstates' varied and often context-specific roles, the committee recognized that an examination of the system's functioning in relation to other transportation modes in serving such purposes as providing access to employment, education, and social activities would require a more granular review than could be provided in this national-level study.

The original planners and builders of the system expected it to have such far-reaching impacts, although they may have discounted the potential for some undesirable outcomes. While the committee gathered much information and heard many opinions about the Interstates' past and current impacts in these areas, it could think of no good way to undertake a prospective economic and social assessment of a system that is already in place and integrated into the country's economic and social fabric. Given that integration, however, it is fair to say that the system's safe, efficient, and reliable operations will be critical to its continued ability to confer crucial economic and social benefits, and that traditional measures of system performance, such as vehicle-to-capacity ratios, crash rates, and person-hours of delay, can offer reasonable indicators of success.

Commissioned Resource Papers

On some important matters, the committee recognized a need for additional information and expert analyses that could not be obtained through briefings alone and that exceeded its members' subject matter expertise. The committee therefore commissioned several resource papers to inform its deliberations and provide the basis for the report's discussion of certain major developments expected to have important implications for the use, condition, performance, investment needs, and funding of the Interstate System. These resource papers, which are provided in Appendixes C through G, consider such issues as the country's future demographic and economic development and the implications for motor vehicle travel, prospects for a dramatically changing climate, and the consequences of technological advances for the vehicle fleet.

Modeling

As stipulated by Congress, the committee consulted the report of NCHRP Project 20-24(79) with respect to the methodology proposed therein for estimating the improvements and investments needed to renew and modernize the Interstate Highway System in the coming decades. The NCHRP report proposes a four-step process for developing these estimates. The first is estimating the investments needed to restore the existing system to a state of "good repair" through targeted resurfacing, restoration, rehabilitation, and reconstruction work.[1] The second step is estimating the additional investments in designs and technologies required to ensure that this restored system operates efficiently through optimized use of its current capacity. The third step is estimating investments that can be made to increase operating capacity through physical changes, including adding lanes and improving interchanges. The final step calls for application of advanced highway and vehicle technology and demand management methods to increase the system's capacity.

The NCHRP report proposes the use of FHWA's long-standing highway and bridge investment modeling systems—the Highway Economic Requirements System (HERS) and National Bridge Investment Analysis System (NBIAS)—for the development of these investment estimates. These models, which are described in greater detail in Appendix H and Chapter 5, are used to perform benefit-cost calculations to determine when an improvement is justified. This is accomplished by calculating the expenditure required to make a given improvement, the condition and performance impact of the improvement (e.g., on pavement smoothness, deck condition, and peak vehicle capacity), and benefits to traffic operations derived from the improved condition and performance. However, the NCHRP report also recognizes that these two models consider only a limited set of improvements. The report therefore proposes that the model results be supplemented with information derived from project case studies and other analytic tools.

In accordance with the wishes of Congress, the committee commissioned a series of analyses of HERS and NBIAS to test whether the four-step

[1] Resurfacing, restoration, and rehabilitation (3R) projects usually involve pavement improvements intended to preserve and extend the service life of existing highways and improve safety. Restoration and rehabilitation work includes such repairs as strengthening roadway bases, shoulder work, and drainage work that enable additional treatments, such as resurfacing, to be done. They typically involve maintaining the existing three-dimensional alignment. "Reconstruction" is defined as rebuilding roadways primarily along existing alignment.

progression of layered improvements described above would enable the determination of investment needs for the future Interstate System. Based on information in the commissioned resource paper on future traffic growth, the models were run using rates of VMT growth ranging from 0.75 to 2.0 percent annually for a period of up to 20 years, as well as for a longer time frame. These analyses led the committee to conclude that the models are not sufficiently robust for investment planning beyond approximately 20 years. The committee also concluded that the proposed four-step progression of investment choices was not a useful approach because decisions on Interstate investments are generally not made on the basis of well-defined calculations of benefits and costs. If they were made in this manner, moreover, they almost certainly would not focus on a prescribed sequence of specific improvement types. Rather, they would generate an ordering based on the most cost-beneficial improvements regardless of type.

Having determined that it would not follow the NCHRP proposal strictly, the committee nevertheless made considerable use of HERS and NBIAS. As a practical matter, there are no substitutes for these systems for providing baseline information on the current condition and performance of the Interstate Highway System. Nor are there substitutes for predicting how changing the level of traffic affects the condition and operating performance of the Interstate System or for estimating the expenditure level associated with specific types of highway and bridge improvements. Thus, while the models' values, algorithms, and output are sometimes simplistic (in ways noted elsewhere in this report), the two models nevertheless are—with some supplementation by other analytic tools[2]—sufficient in the committee's view for making approximations of the investment levels needed over the near to medium terms.

Thus, to make use of HERS and NBIAS required applying plausible rates of traffic growth over the next 20 years and using the models to identify Interstate highway improvements that would be cost-beneficial. Candidate improvements having a calculated benefit-cost ratio of 1 or more would then be categorized as a sound investment and included when calculating total investment requirements. The total is indicative of investment needs in the system; however, it ultimately falls on decision makers to determine whether the investments levels are warranted in light of other demands on resources and in relation to public expectations for levels of traffic delay and pavement and bridge condition.

In sum, the committee acknowledges the limitations of the HERS and NBIAS models regarding levels of system condition and performance, measurement of benefits and costs, and basic algorithms employed. Nonetheless,

[2] The Pavement Health Track (PHT) tool was used to supplement HERS output data. The tool and the analysis are described in Chapter 5.

in keeping with Congress's request for a study employing the methods proposed in the NCHRP report, which center on these models and whose results are routinely presented to Congress, the committee used the models to the extent possible.

Case Studies

Finally, pursuant to the NCHRP proposed methodology, the committee commissioned a set of nearly two dozen case studies of ongoing and planned Interstate projects. These case studies, which are presented in Appendix I, illustrate improvements to the Interstate System currently being made and those that will be needed in the future. The various projects examined in the case studies also provide some additional real-world cost information that could be used to evaluate the cost data obtained from other sources and the analytical models. The case studies, however, did not play as important a role in estimating future system investment needs as originally anticipated because of the difficulty of generalizing from a small number of projects.

REPORT ORGANIZATION

The remainder of this report is organized into six chapters. It is accompanied by appendixes included herein, as well as selected online appendixes.

Chapter 2 provides additional background and context for the study, including a discussion of the history of the Interstate highway program that explains its original purpose, structure, and evolution. Chapter 3 identifies and examines pressing and emerging challenges that, in the committee's view, decision makers will need to confront to prepare the Interstate Highway System for the future. These challenges—ranging from the need to rebuild the system's foundation to preparing for climate change and the substantial infusion of new technology—were gleaned from the committee's outside consultations, the commissioned resource papers, and the expertise and professional judgment of its members. Trends and factors that will shape the nature and magnitude of these critical challenges, from the nation's changing population to the expectations of transformative vehicle technologies, are addressed in Chapter 4.

The special analyses performed by or for the committee are the basis for Chapters 5 and 6. The analysis described in Chapter 5 employed the HERS and NBIAS models, along with some off-model tools and methods, to determine an approximate range of annual investment levels that will be required over the next 20 years to place the Interstate System on a course to meet the critical challenges identified in Chapter 3. The modeling and other analyses reported in Chapter 5 are but a fraction of those that were conducted, but are the most relevant to this study. Chapter 6 reviews the means by which the Interstate System is currently funded and how revenues are allocated. Importantly, this chapter and the complementary Appendix J examine funding options and provide estimates of how each option could generate the revenue levels required to fund the 20-year investment needs identified in Chapter 5.

After summarizing the committee's findings, based on the information, analyses, and assessments contained in earlier chapters, Chapter 7 presents a blueprint for action to maintain the National System of Interstate and Defense Highways as the country's premier transportation system. To this end, the chapter offers 10 recommendations for policy change.

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Abbreviations

FHWA	Federal Highway Administration
TRB	Transportation Research Board

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2

The Vision Takes Root and Pays Off

The founders of the Interstate Highway System relied on a federal–state partnership to build a transcontinental highway system without parallel (McNichol 2003, 8). Their vision spawned a modern freeway system that would eventually crisscross the United States to connect widely dispersed population and commerce centers and support the country's economy and defense needs. In response to proposals from Presidents Franklin D. Roosevelt and Dwight D. Eisenhower, Congress specified the system in 1944 and resolved remaining governance and funding issues in 1956. In a federalist construct that developed after decades of proposals and debate, the federal government took the lead in providing funding and general oversight of the system, while the states developed standards and constructed, operated, and maintained individual highways.

This chapter describes how the founders' vision has been realized through the Interstate Highway System's vast reach and scope, connections with other transportation modes, role in national defense, shared use by travelers and freight carriers, and superior safety performance. Although its founders expected the system to confer large social and economic benefits, they likely could not have imagined how radically it would transform the intercity trucking industry; alter communities; influence the size, shape, and location of the country's metropolitan areas; and become central to the economy and daily lives of virtually all Americans. However, they may have underestimated the social and economic costs that the system's development and operation would impose, especially by transforming urban land use, dividing neighborhoods in the heart of many of the country's largest cities, and increasingly contributing to air pollution and greenhouse gas emissions.

In discussing the key ingredients in the system's success, including its economic and safety benefits, its social costs must also be acknowledged.

THE VISION TAKES ROOT

> Good roads and canals will shorten distances, facilitate commercial and personal intercourse, and unite, by a still more intimate community of interests, the most remote quarters of the United States.
>
> —Albert Gallatin, *Report of the Secretary of the Treasury on Roads and Canals*, 10th Congress, 1st Session, Senate Document No. 205, April 6, 1808, p. 725

Just 1 year after the conclusion of the Revolutionary War, General George Washington had already surveyed a westward route to Ohio and encouraged his compatriots to build a road following this route to unite the new country (McNichol 2003, 14). Indeed, many of the country's founders believed that transportation networks, primarily rivers and canals at that time but also roads, were important for binding the once loosely affiliated former colonies (Weingroff n.d.-a, 183–340). Future presidents and congresses, however, would struggle to realize this vision of a unifying transportation network until constitutional questions about the federal role with respect to interstate roads were resolved at the end of the 19th century, and until the commercial and popular demand for such roads emerged after the advent and embrace of the automobile early in the 20th century.

Throughout the 19th century, and despite numerous proposals for federal involvement in transportation improvements, successive presidents and congresses debated whether the Constitution gave the federal government authority to build or provide funding for canals and highways. Many proposals to do so were vetoed or failed because of a lack of clarity on what the Constitution allowed (Weingroff n.d.-c, 1–75).[1] A strong federal role in interstate highways was not deemed constitutional until an 1893 Supreme Court ruling invoked the Commerce Clause as the basis of federal authority to fund and construct roads (Weingroff n.d.-c, 78–79). Political consensus on this role at the national level, however, remained elusive for decades.

That consensus started to emerge in the early 20th century as demand for highway transportation escalated in the years immediately before and after World War I. Trucking expanded exponentially at the outset of World War I as European powers rapidly increased their imports of U.S. supplies

[1] Note that Congress continued to fund individual improvements through appropriations bills, often over the objections of presidents who viewed this as unconstitutional, but all proposed national programs of funding for highways failed from the time the Constitution was ratified in 1787 until 1916.

to a level that overloaded the capabilities of American railroads (Williamson 2012). Introduction of the Ford Model T one decade earlier had made the automobile affordable to the growing American middle class, and by the 1920s, millions of motor vehicles were plying the country's growing, but still anachronistic, network of public roads.

Land-based transportation in the early decades of the 20th century was characterized by a congested road system, designed and configured for local uses, and punctuated by discontinuities. To alleviate these shortcomings, states such as Maine, New York, and Pennsylvania built and later improved limited-access tolled turnpikes between major cities (Seely 1987). Some of these early tolled highways implemented important new design features, such as the use of bridges to provide grade separation of roads at intersections, that would later be incorporated into the Interstate Highway System. Unlike the tolled turnpikes of the 18th and 19th centuries that suffered public disenchantment and bankruptcy of their operators,[2] the state-operated turnpikes succeeded during this era of burgeoning passenger and freight transportation demand, prompting growing interest in tolling as a highway funding mechanism.

President Franklin Roosevelt, who had earlier promoted building and using roads as governor of New York, was enamored with the concept of a system of tolled transcontinental superhighways. Throughout his first two terms as president, he pondered maps demonstrating various routes, but was reticent about implementing his grand vision because it would not immediately affect Depression-era unemployment and would have been questioned by many in Congress who opposed a federally run highway construction program. The outbreak of World War II created new priorities for the president and Congress, temporarily delaying plans to develop an interstate highway system.

When the end of the war was in sight, interest in developing a high-quality system of interstate highways resurfaced. However, many experts, including his own technical advisors, remained skeptical of Roosevelt's earlier notion of a tolled system (Weingroff n.d.-a, 183–340). Thomas McDonald, the long-serving head of the federal Bureau of Public Roads (BPR), opposed the idea because of the challenges of obtaining rights-of-way, a compelling need to help states fund safety improvements on existing roads, and the priority of alleviating the local congestion problems arising in the country's rapidly suburbanizing cities. McDonald also questioned whether there would be sufficient demand for long-distance trips by highway, as BPR's analysis indicated that toll strategies would not work for large portions of a national system crossing lightly populated rural

[2] "By 1830, more than 8,000 miles of roads had been built or converted to turnpikes under state charters of incorporation" (Williamson 2012, 3).

areas and were better suited for limited circumstances such as high-demand, urban segments (Weingroff n.d.-a, 299–307).

In 1943, Roosevelt's National Interregional Highway Committee recommended constructing a 40,000-mile Interstate Highway System, which was authorized by the Federal-Aid Highway Act of 1944. The designated system was to be based on enhanced design standards developed by the states with 50 percent federal funding. While the 1944 act generated scant mileage, in part because the states in the waning years of World War II had few resources to devote to constructing new highways, it reinforced a precedent set years earlier by the Federal Road Act of 1916 by delegating decision making about roads to the states while retaining federal authority to restrict federal aid to a subset of state highways having interstate functions (Weingroff n.d.-b).[3] With the idea of a tolled interstate highway network gaining no traction, the Interregional Highway Committee proposed a national system of "free" highways that, together with the assurance of sufficient state control, would form the basis for compromises within Congress.

Those compromises, forged under the leadership of President Eisenhower, led to passage of the Federal-Aid Highway Act of 1956, popularly known as the National Interstate and Defense Highways Act (Weingroff n.d.-c). The legislation required that the Interstate Highway System connect, by routes as direct as practicable, the principal metropolitan areas,[4] cities, and industrial centers; serve national defense; and connect all suitable border points with routes of continental importance. The 1956 act's passage hinged on the system being funded on a "pay-as-you-go" basis, with revenues obtained from highway user fees, primarily in the form of federal fuel taxes and various truck fees and taxes. The revenues would be placed in a Highway Trust Fund (HTF) with a guarantee that the funds would be dedicated to federal-aid highway projects, including specific funding solely for the development of the Interstate System. With revenues from the HTF, the federal government would reimburse states for 90 percent of the cost of construction. While the act limited the system to 41,000 miles, it authorized the inclusion of some existing toll highways that would not be eligible for HTF funding.

Important for ensuring system connectivity, the program assured states that they would ultimately be provided the federal aid needed to complete a planned route, known as "cost-to-complete" assurance. That federal funding would be capped, however, based on an estimate of the cost to complete, which entailed segment-by-segment projections of investment

[3] "Post roads" are mentioned in the Constitution as under federal authority, but by the 20th century, the roads on which post offices were located were not necessarily major thoroughfares or interstate in character.

[4] "This National System of Interstate Highways, although it embraces only 1.2 percent of total road mileage, joins 42 state capital cities and 90 percent of all cities over 50,000 population" (Eisenhower 1955, 2).

requirements. The first cost-to-complete agreement (known as the Interstate Cost Estimate, or ICE) was generated in 1958 at $37.6 billion and subsequently approved by Congress (Weingroff n.d.-d). Under the agreement, ICEs would need to be updated with each authorization cycle.

ADVENT AND EVOLUTION OF THE INTERSTATE SYSTEM

With passage of the 1956 act, the states embarked on the world's largest construction project, an undertaking that would quickly produce observable consequences by shaping household travel patterns, transforming the long-haul trucking sector, and contributing to the decentralization of metropolitan areas. To help constrain total spending, the 1956 act had limited the total mileage that could be built with federal aid (FHWA 2017a). Subsequent reauthorizations added increments of mileage to the original system. For example, the Surface Transportation Assistance Act of 1978 included approval for a total of 43,000 miles for use of Interstate Construction (IC) funding (FHWA 2017a, n.d.-a).

One of the hallmarks of the Interstate Highway System is its uniformity across states. The 1956 act required that the system be built using common geometric and construction standards, as well as other features such as consistent signage. The specific standards were developed by the American Association of State Highway and Transportation Officials and adopted by the BPR and its successor agency, the Federal Highway Administration (FHWA). The standards included the following requirements:

- Full control of access to the facilities,
- Minimum spacing between full-control access interchanges of 1 mile in urban and 3 miles in rural areas,
- Design speeds of 50 to 70 miles per hour (depending on type of terrain),
- A minimum of two travel lanes in each direction,
- 12-foot lane widths,
- 10-foot right paved shoulders,
- 4-foot left paved shoulders,
- 16-foot vertical clearance for structures (originally set to meet military deployment needs), and
- Common signage.

Research activities, such as the American Association of State Highway Officials Road Test, also played a key role in providing the basic durability requirements for Interstate pavements, including their 20-year design life, as well as for the impact of highway traffic on the durability of bridges (Hallin et al. 2007; Highway Research Board 1962).

With these basic system standards and a funding mechanism in place, construction of the system began almost immediately after passage of the 1956 act, leading to a revolution in road-building technology and activity. Within a few years of the awarding of the first contracts to build the system in late 1956, states would end up moving more than 10 times the volume of earth required to build the Panama Canal, and they would pour enough concrete to build a wall 9-feet thick and 50-feet high and long enough to encircle the world (Arave 2003). By the 10th anniversary of the system's authorization, the states had opened more than 22,000 miles to traffic and had an additional 6,400 miles under construction—representing more than half the planned system (FHWA 1985, 163).

By 1966, mileage had been built and was under construction in every state in the continental United States, but with many gaps between segments. Those gaps would be reduced within a few years, but would take some time to close completely; indeed, one of the major transcontinental routes in the system, I-80, was not finished until 1986 (McNichol 2003, 119).

This first half of the Interstate Highway System could be built so quickly because much of it passed through open rural areas (McNichol 2003, 116–117, 126–133). It also incorporated some highways that had been built years earlier. For example, a portion of Grand Central Parkway in Queens, New York, was opened to traffic in 1936 and later was incorporated into the Interstate System as part of I-278. The Pennsylvania Turnpike between Irwin (southeast of Pittsburgh) and Carlisle (west of Harrisburg) opened in 1940 and was later designated as I-76 and I-70. The bulk of the second half of the Interstate System, which would traverse the most difficult terrain and cross urban areas, would take another 30 years to complete (McNichol 2003, 112). In fact, the original plan was recently completed, as the last discontinuity, a segment of I-95 on the border of Pennsylvania and New Jersey, was finalized in 2018 (Sofield 2018).

As the construction phase of the Interstate Highway System passed its zenith in the 1970s—and some early segments were beginning to show their age and wear from the stress of heavy use—Congress modified key aspects of the original Interstate program. The 1976 Federal-Aid Highway Act provided, for the first time, funding for the "3Rs"—resurfacing, restoration, and rehabilitation.[5] Reconstruction would become an eligible expense in 1981, creating the "4Rs."[6] While all Interstate maintenance had previously

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[5] 3R projects usually involve pavement improvements intended to preserve and extend the service life of existing highways and improve safety. Restoration and rehabilitation work includes such repairs as strengthening of roadway bases, shoulder work, or drainage work so that additional treatments, such as resurfacing, can be done. They typically involve maintaining the existing three-dimensional alignment.

[6] **Reconstruction** is defined as applying to roadways that are rebuilt primarily along existing alignment.

been the responsibility of states, a consensus had developed that it was in the national interest to provide federal funding for preservation[7] as distinct from basic maintenance activities, such as snow removal and pothole repair, which would remain the exclusive responsibility of states.

Successive changes in law would further modify the Interstate program by phasing out the dedicated highway construction program and by making the Interstates a subset of a much larger set of highways eligible for federal aid. In the face of uneven completion of the system among states, Congress modified the federal-aid funding formula by providing each state a minimum of 0.5 percent of the total Interstate construction apportionments. If not needed for new Interstate construction, states could use the funds for Interstate 4R work, as well as for work on other highways eligible for federal aid. With passage of the Intermodal Surface Transportation Efficiency Act of 1991, Congress declared that the Interstate construction funds provided during that authorization period would be the final ones to complete the system. In 1995, Congress designated the National Highway System (NHS), a 160,000-mile system that included the Interstates (Bennett 1996). The NHS is intended to include all highways with interstate transportation functions, even if they do not meet the specific design standards of the Interstate Highway System.

With the advent of the NHS, the Interstate Highway System became one of several categories of roadways eligible for federal assistance, which also include the other 174,000 miles of non-Interstates in the NHS[8] and an additional 800,000 miles of intrastate and interstate routes of lowers category (see Figure 2-1), for a total of around 1 million miles. In legislation passed in 2012, Congress consolidated funding for NHS projects under a newly established National Highway Performance Program (FHWA 2016d). Of federal highway aid funding committed to projects in 2014, about 30 percent went to projects on the Interstate System.[9]

Today, the Interstate Highway System, as shown in Figure 2-2, consists of more than 49,000 miles, including multiple transcontinental routes,

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[7] "Preservation consists of work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair. Preservation activities generally do not add capacity or structural value, but do restore the overall condition of the transportation facility" (FHWA 2016c).

[8] In 2012, Congress expanded the NHS by designating an additional 60,000 miles through Section 1104 of the Moving Ahead for Progress in the 21st Century Act (MAP-21) (FHWA n.d.-b).

[9] Federal highway legislation offers states considerable flexibility in how they spend federal aid (it is not allocated by highway class). In fiscal year 2014, state obligation of federal aid to the Interstate Highway System totaled about $11.2 billion (31 percent) out of about $35.4 billion in federal highway aid provided to the states (see FHWA 2016e, Table FA-4C). Because about 15.5 percent of the federal gas tax is dedicated to transit, the share of total federal fuel taxes allocated to the Interstates would be less than one-third of total federal aid for surface transportation derived from fuel taxes.

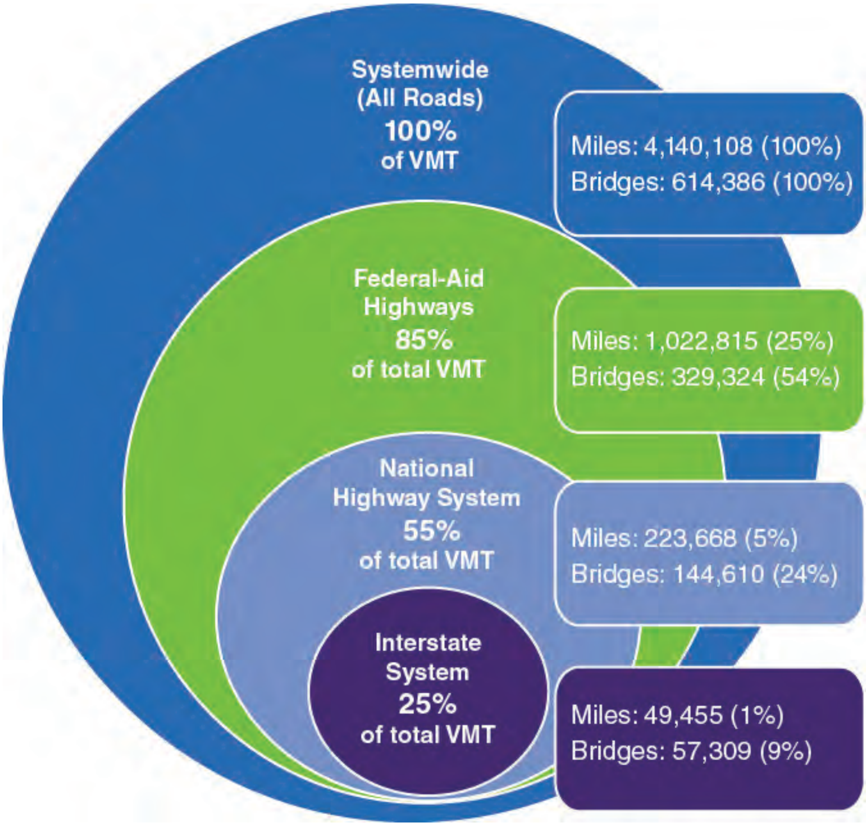

FIGURE 2-1 Extent of the Interstate Highway System in comparison to the rest of the road network as of 2017.
NOTE: Mileage based on FHWA. VMT = vehicle-miles traveled.
SOURCES: FHWA 2017b; n.d.-c, Table 3; n.d.-d.

segments in all 50 states, and connections to all major urban areas of the continental United States. All told, the system's construction, which was in 1955 expected to take 12 years to complete with an investment of about $27 billion ($252 billion in 2018 dollars) for 40,000 miles, would take more than 40 years to reach near-completion and a total state and federal investment of $114 billion ($209 billion in 2018 dollars) for the 42,795 miles originally planned (Rose 2003; Weingroff n.d.-d; Weiss 2008).[10] Fig-

[10] The final cost of the construction of the Interstate was estimated in 1991 as $114.3 billion (FHWA 2017a). The inflation-adjustment index published by the Federal Reserve Bank of Minneapolis was used to compare costs from 1955 and 1991 (Federal Reserve Bank of Minneapolis n.d.).

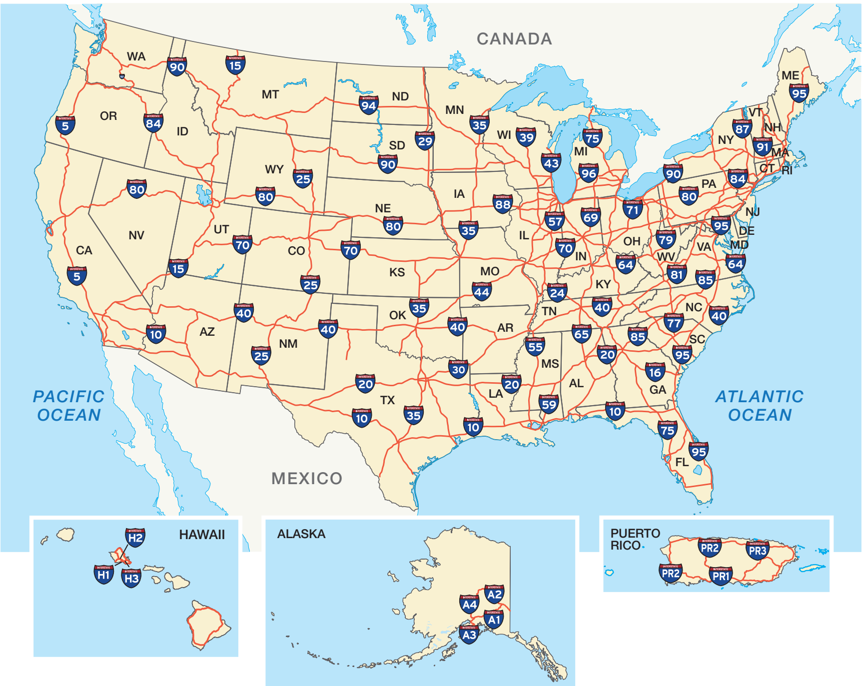

FIGURE 2-2 Route map of Interstate Highway System, 2017.

ure 2-3 illustrates how Interstate centerline- and lane-mileage have changed since 1990, when the system was considered largely complete.

A BOON TO PASSENGER AND FREIGHT TRANSPORTATION

At a Glance

- The Interstate Highway System accounts for about one-quarter of all miles traveled by light-duty vehicles and 40 percent of all miles traveled by trucks.[11]
- The system has accounted for significant travel savings for interstate and long-distance travel for both passenger vehicles and freight, in some cases reducing travel time by half compared with travel times before its construction.
- The Interstates not only serve as the backbone of the country's highway system but also connect to its marine ports, railroad terminals, and commercial airports.

[11] This figure includes single-unit and combination trucks; it does not include pickup trucks.

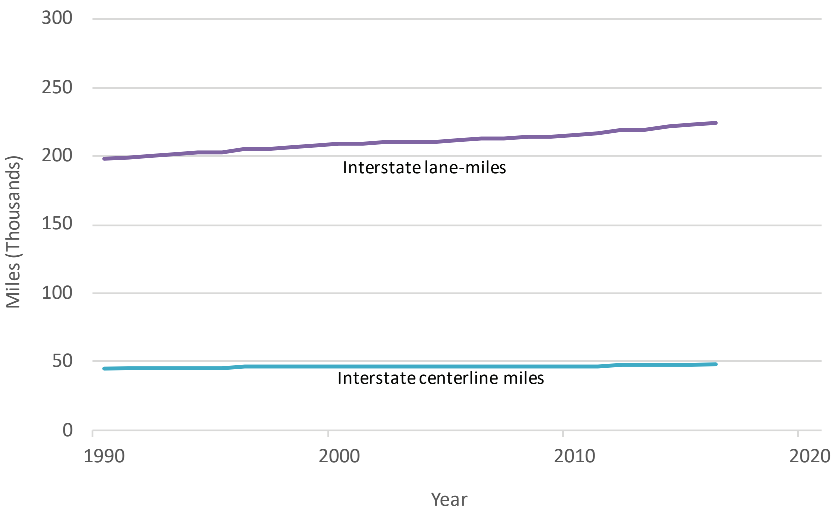

FIGURE 2-3 Interstate mileage, 1990–2017.
SOURCES: FHWA 2017g, Table FI-220; 2017h, Table HM-60.

Motorists flocked to the Interstate highways as soon as they were opened to traffic, and that popularity has by no means waned. By 1967, Interstate routes already carried 12 percent of the country's vehicle-miles traveled (VMT) (FHWA 1967, 2017d). The Interstate Highway System today represents little more than 1 percent of public road linear miles and 2.5 percent of lane-miles, accounting for about one-quarter of all VMT (21 percent of all light-duty vehicles traffic and 40 percent of all truck traffic[12]) (FHWA 2017e, Table VM-1).[13] More than half of the miles traveled by combination trucks—used mostly for freight carriage—occur on the system (FHWA 2017e, Table VM-1).

A clear reason for the popularity of Interstate Highway System is that it has been instrumental in reducing travel time for both personal travel and the movement of freight. To illustrate, driving time from Los Angeles to Washington, DC, from Memphis to Atlanta, or from Boston to Miami was reduced by almost half compared with the pre-Interstate era (see Table 2-1).

According to the American Travel Survey, which was last updated in 1995, nearly one-quarter of long-distance trips by highway (mostly by Interstate highway) were made for business-related purposes, but three-quarters were made for nonbusiness (including commuting) and recreational

[12] Single-unit and combination trucks.

[13] Most travel in light-duty vehicles is personal in nature (see AASHTO 2013, Table 21; FHWA 2016a, Table VM-2; 2016b, Table VM-4).

TABLE 2-1 Example Comparisons of Driving Distance and Time in 1955 on Non-Interstate Routes and in 2018 on Interstate Routes

	Driving Distance (miles)		Driving Time (hours:minutes)		Approximate Reduction in Driving Time (%)
City Pair	1955[a]	2018[b]	1955[a]	2018[b]	
Los Angeles to Washington, DC	2,940	2,660	72:00	39:00 (partially tolled)	46
Boston to Miami	1,655	1,492	44:20	22:45 (partially tolled)	49
Salt Lake City to Chicago	1,484	1,399	32:50	20:20 (partially tolled)	38
Denver to Saint Louis	899	850	19:00	12:15 (partially tolled)	36
Boston to New York City to Washington, DC	450	442	12:40	7:40 (partially tolled)	39
San Francisco to Los Angeles	405	383	10:05	6:25	36
Memphis to Atlanta	403	385	10:35	5:45	46

[a]Calculated from data from 1955 United States Mileage Chart. American Automobile Association.
[b]Data from Google maps.

purposes (TRB 2016). These figures demonstrate the broader impact of the Interstate System beyond its commercial usage.

Travel-time savings to the country's freight sector have also been large, contributing to marked growth in long-haul truck traffic. For example, trucks moved about 17 percent of ton-miles in the mid-1950s (Weingroff, n.d.-c); by 1980, this share had almost doubled to 30 percent, and by 2015 it had reached almost 40 percent (BTS 2017). Figure 2-4 displays the Interstate System in red lines whose thickness is proportional to the average volume of daily truck traffic.

The Interstate highways also play a vital role in connecting other freight modes. Figure 2-5 shows a map of the highway corridors (in red) that the U.S. Department of Transportation (U.S. DOT) has identified as part of the National Highway Freight Network. Routes on this national network are viewed as deserving of strategically directed federal resources and policies to improve the performance of the country's overall freight system. Most

FIGURE 2-4 Average daily long-haul truck traffic on the Interstate Highway System, 2015.
NOTE: Long-haul freight trucks typically serve locations at least 50 miles apart, excluding trucks that are used in movements by multiple modes and for mail.
SOURCE: FHWA 2017.

of the highways identified are Interstate routes, which are instrumental in serving the country's marine ports and commercial airports, as well as connecting major freight rail hubs.

BROADER ECONOMIC AND SOCIAL CONSEQUENCES

At a Glance

- Analyses of the economic returns to Interstate and other highway investments in the United States have found high net social rates of return.
- Urban Interstates and other freeways contributed to suburbanization and the depopulation of many major U.S. cities.
- When the Interstates were being planned, many state and local officials believed the urban portions would reduce congestion and help save declining central business districts, which was not always the case. Today, some metropolitan areas are considering mitigations, such as covering urban Interstate segments or placing them in tunnels to reunite divided communities.

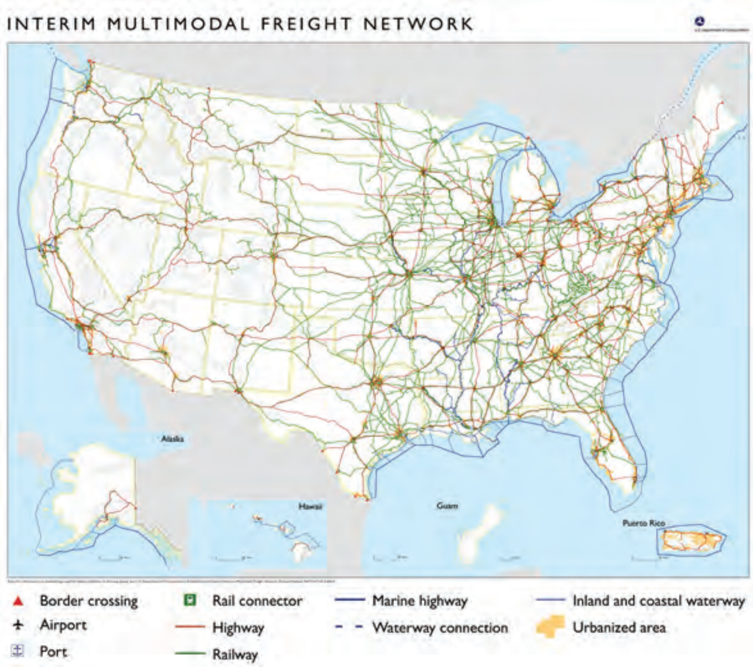

FIGURE 2-5 Multimodal freight network.
SOURCE: U.S. DOT 2016.

> More than any single action by the government since the end of the war, this one would change the face of America with straightaways, cloverleaf turns, bridges, and elongated parkways. Its impact on the American economy—the jobs it would produce in manufacturing and construction, the rural areas it would open up—was beyond calculation.
>
> —Dwight D. Eisenhower, *Mandate for Change*, 1963 (FHWA n.d.-e)

President Eisenhower's assessment of the Interstate Highway System's far-reaching impact appears to have been justified. In the more than 50 years since he offered the assessment, the system has become even more integrated into the U.S. economy and lives of Americans. With the benefit of hindsight, it can be seen that the original Interstate System had important catalyzing impacts—going beyond where traffic demand was foreseeable to influencing future economic development and its location. As a result, the United States has managed to overcome the disadvantage of the long distances that separate many regions of the country. This benefit not only has enabled the country to employ its rich array of human and natural resources to compete in global markets, but also it has helped integrate national, multistate, regional, and local economies as they have capitalized on the system's connections, travel speed, and capacity advantages.

Regions previously not well connected to the national economy have become more closely linked by the Interstate System for both the movement of goods and personal travel. The system has shaped the economics of residential, commercial, and industrial locations throughout the nation. It has expanded business's access to labor markets and allowed people to commute farther to their workplaces, which in turn has opened up more land around cities for housing and commercial development. Improved access has allowed businesses to restructure their operations and locations to increase efficiency. For instance, the faster trucking service made possible by the Interstate System has allowed firms to rely on fewer and larger production and distribution centers to reach markets and reduce inventories (Louis Berger International 1995, 15–16).

These impacts can be difficult to quantify. However, analyses of the economic returns to highway investment in the United States, in general, have found a high social rate of return. That return was highest during the post–World War II expansion of the country's overall highway network (Nadiri and Mamuneas 1996).[14] During the 1950s and 1960s, when much of the Interstate System was constructed, economic returns on highway investments have been estimated as averaging 50 to 60 percent. Moreover, analyses indicate that almost every sector of the economy experienced significant economic gains as a result of highway investments (Mudge 2018, 19–20). The trucking industry, whose fortunes are tied most closely to high-quality highways, is estimated to have reaped especially large productivity benefits from federal investments in Interstate highways. Between 1950 and 1973, when the Interstate System took shape, these returns to the trucking industry alone were so large that they could justify one-third to one-half of the federal-aid investment over this 23-year period (Keeler and Ying 1988).[15]

It is generally understood that urban Interstates and other freeways contributed to suburbanization and the depopulation of many major U.S. cities, which accelerated after World War II in concert with an expanding middle class and the fast-growing personal motor vehicle fleet.[16] Although many other factors were at work, the Interstate System facilitated greater dependence on the automobile for commuting to work and other household and social activities. Interstate "beltways" were built on the outskirts of

[14] See also Mudge's (2018) recent interpretation of these results. Note that one would expect the correlation between overall interstate highway investment and economic returns to decline after a network has been built and in place. At that point, the economic contribution of the network is based on its performance and connectivity and the way it continues to affect the geography of economic activity, as described in the previous paragraph.

[15] Note that the authors of this report intentionally ended their period of analysis in 1973 in order to exclude the effects of transportation deregulation.

[16] This section is drawn from a literature review and literature cited in TRB (1998).

many cities for the purpose of redirecting longer-distance, interstate traffic around urban areas and congested central business districts (CBDs), but these highways quickly became heavily used for local traffic. The 1970s and 1980s saw a building boom of commercial and residential development along these highways, such that by the 1990s, the majority of office space in many metropolitan areas, such as Boston, Dallas, Denver, San Diego, and St. Louis was located outside the traditional CBD (FDIC 1997; FRED n.d.). By this time, Interstates alone carried 26 percent of daily VMT within urbanized areas, and the most common commute was no longer from suburb to CBD but from suburb to suburb (Pisarski 2006).

These changes in the economic development patterns of metropolitan areas reflected the time and cost savings provided by highways and helped metropolitan areas became vital centers of economic activity. However, the effects of urban Interstates were not entirely beneficial for center cities and their neighborhoods. The postwar mass movement of people and employers to the suburbs led to the loss of center city population, a declining housing stock, and impoverished urban neighborhoods (TRB 1998). Even before planning began to bring Interstates routes into cities, officials at all levels were calling for urban renewal programs to clear "blighted" areas and to introduce urban expressways to reduce congestion and save declining CBDs (Mohl 2004, 678). The federal government thus provided funding through the Interstate and urban renewal programs to implement plans for direct freeway access to central cities. The Federal-Aid Highway Act of 1956 changed the funding formula for highway construction from the 50/50 percent share of federal and state funds previously authorized under the Federal Highway Act of 1916 to a 90/10 percent ratio for Interstate projects. Coupled with state preemption of local transportation planners and city officials in locating Interstate routes, this funding change gave state highway agencies greater capacity and incentive to build urban Interstates, often without consulting or coordinating with affect cities (Taylor 2000).

Until the 1970s, when stronger federal provisions requiring more consultative highway planning took effect, cities without the ability to alter state highway plans often experienced the loss of their neighborhoods to accommodate the new urban freeways, often before residents had the opportunity or wherewithal to resist (AMPO n.d.). Many of the routes harmed low-income, often minority, neighborhoods. In downtown Miami, for example, a 30-square-block interchange displaced more than 10,000 mostly African American residents and fragmented the once-thriving Overtown district next to the CBD (Mohl 2004, 688). In New Orleans, Interstate 10 was built "straight through a poor black neighborhood" (McNichol 2003, 155). The governor of Michigan blamed the destructive 1967 Detroit riots primarily on the siting of urban Interstates through minority neighborhoods (McNichol 2003, 155). Similar impacts in other cities led civic associations, civil rights leaders, and historic preservationists to begin pushing back in what became known as the "Freeway Revolt" in a dozen or more cities during the 1960s and 1970s.

The damage done to the social fabric and economic vitality of many cities by urban freeways that split and isolated neighborhoods persists to this day, leading some states and metropolitan areas to plan and take mitigative actions to reunite communities. The Embarcadero in San Francisco, the Central Artery Tunnel in Boston, and the I-95 Penn's Landing project in Philadelphia[17] are examples of projects intended to replace, place below grade, or cap Interstate highways for the benefit of local communities while maintaining the highways' functionality.

ROLE IN NATIONAL DEFENSE

The U.S. Department of Defense (DoD) transports much of its heavy equipment and supplies by freight rail for long distances domestically. However, the Strategic Highway Network (STRAHNET) also is critical to DoD's logistics, including emergency mobilization plans and peacetime movements of heavy armor, fuel, munitions, parts, and food. The network, shown in Figure 2-6, was developed by DoD in collaboration with FHWA and state DOTs. It includes the entire 49,000-mile Interstate Highway System and another 15,000 miles of other major highways (FHWA 2017c). It also includes another 2,000 miles of lesser state and local roads that link military installations and marine ports to major highways. DoD's 2012 Strategic Seaports Study concluded that most existing STRAHNET highways connecting strategic seaports are adequate to support today's and foreseeable DoD deployments (DoD 2012).

SAFETY BENEFITS

At a Glance

- The Interstate highways are the safest roads in the country per vehicle-mile traveled.
- Reconstruction presents opportunities to enhance the safety performance of the Interstates through the use of modern highway designs with known safety benefits, including advanced electronic technologies once proven to confer such benefits.

[17] I-95 in Philadelphia—$225 million total investment to cap a section of Interstate 95 (Delaware River Waterfront 2017).

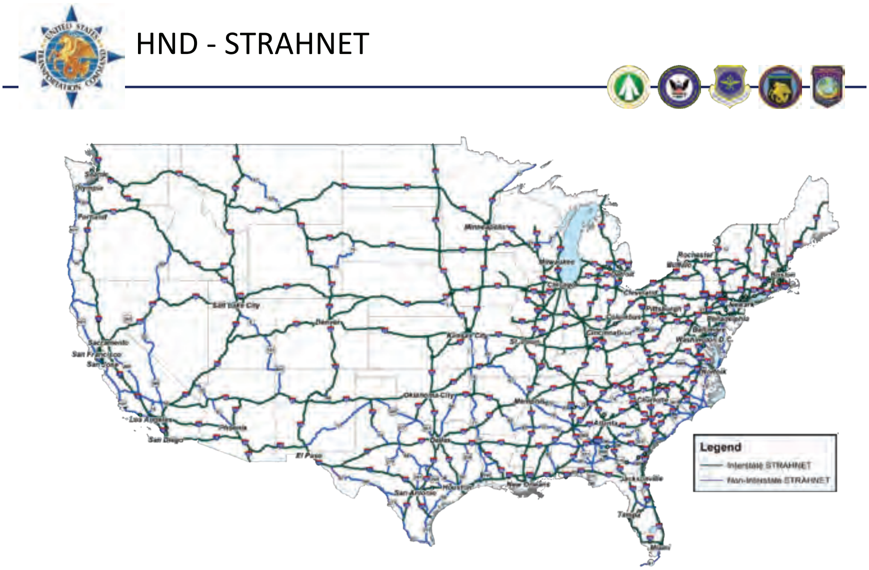

FIGURE 2-6 The Strategic Highway Network (STRAHNET).
SOURCE: Map shared by Busler 2017, 13.

The Interstate Highway System was designed to provide not only efficient but also safe transportation. Full access control—one of the key features of Interstate highways—is perhaps the most significant design feature effective in lowering crash rates (AASHTO 2011). Many other features contribute, including some found on other high-quality freeways, such as clear zones on roadsides; wide lanes and shoulders; straighter geometries with superelevated curves; and an emphasis on good lighting and drainage, familiar and legible signage, and the maintenance of pavement markings.

Per mile traveled, the Interstate System is the safest highway network in the United States. Compared with other road types, Interstate fatality rates are the lowest on both rural and urban routes. In 2016, the United States experienced 37,740 traffic fatalities, 5,054 (about 13 percent) of which occurred on the Interstates (FHWA 2017f, Table FI-220)—this despite their relatively high travel speeds and 25 percent share of VMT. Given the 805 billion miles traveled on the Interstates in 2016 (FHWA 2017e, Table VM-1), this fatality figure represents a rate of 6.3 deaths per billion miles of travel. In contrast, the fatality rate on all other public roads in that same year was 13.2 deaths per billion VMT.[18] It has been estimated

[18] Calculated from data from FHWA (2017e, Table VM-1; 2017-f, Table FI-220).

that since 1967 when the Interstate System was little more than a decade old, more than a quarter-million additional deaths would have been experienced had all the miles traveled on the Interstates been traveled on other roads with their higher rates of fatal crashes.[19]

Nevertheless, more than 5,000 deaths per year is a serious public safety concern, and the Interstates continue to be the focus of efforts to increase their safety performance. Ensuring the safety of work zones is a particular consideration, and one that may become even more challenging as the system undergoes more repair and reconstruction work and as traffic volumes increase. Interstate entrance and exit ramps can be especially hazardous where they merge with surface streets having considerable pedestrian and bicycle traffic. Indeed, about 14 percent of fatalities on urban Interstates involve pedestrians and bicyclists, often in the vicinity of these entrance and exit ramps.[20]

SUMMARY

This chapter has described how the original vision for the Interstate Highway System was realized through the system's vast reach and scope, connections with other modes, shared use by travelers and freight carriers, support for national defense logistics, and high safety performance. Key points are summarized below.

The Interstate Highway System was originally funded on a "pay-as-you-go" basis, with revenues obtained from highway user fees, primarily in the form of federal fuel taxes and various truck fees and taxes. The revenues were to be placed in a Highway Trust Fund (HTF) to be used exclusively for federal-aid projects; of those total funds, the 1956 Act carved out specific funding dedicated to Interstate highway planning and construction.

The Interstate System was designed for uniformity across states. The 1956 act that created the system required that it be built using common geometric and other design standards, as well as uniformity of other features such as signage. The legislation also required that the Interstate System connect the country's principal metropolitan areas and industrial centers; serve national defense; and provide all suitable border points with routes of continental importance.

As the construction phase of the Interstate System passed its peak in the 1970s and 1980s and some early segments were deteriorating from heavy use, Congress modified key aspects of the original Interstate program by

[19] Traffic fatality calculations and rates were provided by the Insurance Institute for Highway Safety.

[20] Analysis provided by the Insurance Institute for Highway Safety based on data from U.S. DOT's Fatality Analysis Reporting System (FARS).

allowing the use of federal-aid funds for purposes other than new construction, including resurfacing, restoration, rehabilitation, and reconstruction of existing segments. Congress also made HTF funds available for spending on other highways and public transit. In 2014, about 30 percent of total federal highway aid from the HTF was allocated to the Interstate System.

The Interstate System accounts for about one-quarter of all miles traveled by light-duty vehicles and 40 percent of all miles traveled by trucks. The Interstates have a vital role in serving the country's marine ports and commercial airports, while also having connections with major freight rail terminals.

The Interstate System has had a mixed record of impact on the country's metropolitan areas. The system has been vital to connecting metropolitan areas and as commuting and commercial traffic corridors, spurring business and residential development. However, it is now widely believed that urban Interstates and other urban freeways also contributed to suburbanization and the depopulation of many major cities. When the urban Interstates were being planned, many officials believed they would reduce congestion and help save central business districts. Some metropolitan areas are now trying to remedy the adverse effects of freeways, some that have divided and isolated communities, through means such as covering or capping segments.

Interstate highways are the safest roads in the country per vehicle-mile traveled. Many factors contribute to the system's safety, including wide lanes and shoulders and straighter geometries with superelevated curves. An especially important feature is the system's full access control. As the system undergoes repair and reconstruction, ensuring the safety of work zones will be a challenge. Reconstruction also presents opportunities to enhance the safety of the Interstates through the use of modern design standards and other features that confer known safety benefits.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AMPO	Association of Metropolitan Planning Organizations
BTS	Bureau of Transportation Statistics
DoD	U.S. Department of Defense
FDIC	Federal Deposit Insurance Corporation
FHWA	Federal Highway Administration
FRED	Federal Reserve Bank of St. Louis
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation

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3

Emerging Challenges

Having served as the backbone of the country's transportation system for more than half a century, the Interstate Highway System is aging and in many places is worn and congested. Nonetheless, it is being counted on to serve as that backbone for decades to come. States face a number of challenges to ensure that it can do so, some that have long been apparent and will almost certainly require near-term attention, and others that are only now becoming evident but have the potential to be even more demanding and transformative in their effects.

Critical challenges that have been apparent for many years include the need for a massive renewal of the system's deteriorating foundations[1] and upgrades to its capacity to accommodate and manage already high traffic volumes that are continuing to grow and shift in location. More than half a century of intensive use has taken a toll on the system. Once a showcase of modernity, the Interstates now contain tens of thousands of miles of pavement that have been subject to age and wear with little more than periodic resurfacing and modest additions to capacity—all in the face of marked increases in use. A backlog of repairs to deteriorated foundations and chronic traffic delays have come to plague the system's most heavily traveled urban routes, where demand and capacity are often unmanaged. Although the system has long been considered complete in its national

[1] The purpose of pavement and bridge foundations, which consist of the subbase and its associated strengthening materials, is to transfer the loading from the pavement or bridge structure to the soil or subgrade.

and interregional coverage and connectivity, shifts in the geography of the country's population and economic activity are creating demands for the addition of new nodes and links, and in some cases for the modification or replacement of urban segments viewed as unduly intrusive to communities.

Even as these long-standing but increasingly pressing challenges demand attention, new ones are emerging that may prove even more vexing. Continued advances in technology—ranging from more efficient and faster construction methods and more durable materials to electronic tolling and increasingly connected and automated vehicles[2]—could make the rebuilding of the Interstate System and the allocation of its capacity more manageable while furthering the continual goal of increasing safety. Rapidly changing technologies, however, could also create new challenges, such as ensuring that the system's operations do not become prone to new safety risks and are secure from cyberattacks. Such eventualities will almost certainly take place within the context of a changing climate that will compel transportation agencies to make the Interstate System increasingly resilient to damage and disruptions resulting from rising sea levels and extreme weather events. In addition, there is the imperative to modernize the Interstate Highway System in a manner that contributes to reducing greenhouse gas (GHG) emissions to levels needed to avoid the worst impacts of climate change.

While exactly how these developments will evolve over the next several decades remains uncertain, there is little question that they will present significant challenges. The need to rebuild the system's foundation and rationalize its capacity is inevitable, as are major changes in technology and climate as the Interstate System moves deeper into the 21st century. This chapter describes these challenges in general terms, while the next chapter considers them in the context of the country's changing demographic, economic, climate, and technological landscape.

[2] The term "connected vehicles" refers to vehicles that incorporate technologies that allow them to communicate with other vehicles, facilities, or persons with the same technology. Automated vehicle systems, on the other hand, include technologies that do not rely on communication with other entities but relieve drivers of some or all of the tasks associated with controlling the movement of the vehicle.

REBUILDING THE SYSTEM'S FOUNDATION

At a Glance

- As the foundation of a pavement continues to deteriorate, resurfacing will no longer rectify the damage, and the pavement structure will need to be rebuilt from the subbase up.
- Most segments of the Interstate Highway System retain their original underlying structure. Thousands of miles are past due for a complete rebuild; thousands more will become due in the next 20 years.
- Repeated pavement resurfacing can produce higher life-cycle costs relative to full-depth periodic pavement reconstruction.
- Even the newest segments of the Interstate System will need to be rebuilt in the next 20 years. If the entire 49,000-mile system is to be rebuilt over this period, an average of more than 2,400 miles will need to be rebuilt each year.
- Today, more than one-third of Interstate bridges have been in service for more than 50 years. They will require investments that will add significantly to the challenge of renewing the system's pavement foundation.

Most of the miles of highway on the Interstate Highway System are more than 40 years old, and about one-third are more than 50 years old. Nearly all have been resurfaced, often multiple times. In most cases, however, their foundations have not been rebuilt, despite decades of stress from high traffic levels that were largely unanticipated in their designs (Hallin et al. 2007, 9). The condition of a pavement foundation is affected by a variety of factors, including traffic volumes and loadings, construction quality and materials, design details, drainage effectiveness, soil properties, and freeze–thaw conditions along with the deleterious effects of deicing chemicals (TRB unpublished). When a pavement foundation deteriorates, the effects eventually become manifest at the surface as cracked, rutted, and spalled top layers that must be repaired and resurfaced at shorter intervals to regain smoothness and serviceability. As the foundation continues to deteriorate, surface repairs will no longer rectify the damage, and the pavement structure will need to be rebuilt from the subbase up (see Figure 3-1).

The pavements on many of the Interstate System's older segments had reached the end of their design lives before 1980, even as the final planned segments of the system were being built. Now, even the pavements built in the 1980s and early 1990s, at the end of system's original construction phase, have reached or will soon reach the end of their design lives. In those

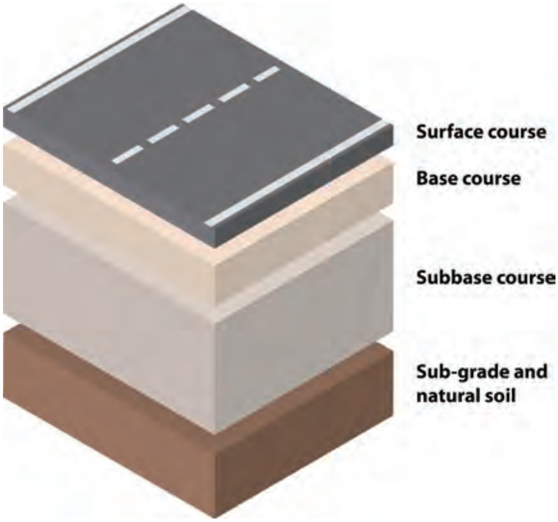

FIGURE 3-1 Simplified highway cross section.
NOTE: For the purposes of this report, the sub-base course and sub-grade and natural soil cross sections are considered components of the foundation as they relate to investment in reconstruction.

cases in which Interstate segments have already undergone full reconstruction, the work was typically undertaken for reasons in addition to pavement serviceability, such as to add traffic capacity and safety upgrades. While the number of lane-miles on the system that has undergone full reconstruction is not documented, it is reasonable to conclude that fully rebuilt segments account for only a small percentage of total system lane-miles and that most segments have their original substructure. Accordingly, thousands of miles of Interstate highway are past due for a complete rebuild, and thousands more will become due over the next 20 years.

Federal laws and policies, which have emphasized different priorities, have contributed to this deferral of reconstruction work. For the first 20 years of the Interstate highway program, federal highway funds, by law, could be used only for new construction and full reconstruction. That policy was changed, however, when the Federal-Aid Highway Act of 1976 authorized states to use federal funds for major repairs and partial reconstructions to keep the deteriorating portions of the highway system serviceable. As a result of this policy change, federal funds could be used for Interstate highway pavement resurfacing and rehabilitation. States welcomed the change because the cost of fully reconstructing damaged pavements to new standards had escalated, heavy traffic demands had complicated the planning and execution of such projects, and the number of highway segments sustaining surface damage had grown steadily as the stressed system aged (TRB 1987, 14–16). States thus devoted most of their federal aid to new construction and surface maintenance, but at the cost of repeatedly deferring the needed replacement of their aging and damaged highway foundations.

The circumstances that contributed to this change in federal policy had not been anticipated by the original planners of the Interstate System. When Congress first funded Interstate construction in 1956, it required states to plan and design for the traffic levels expected in 1975 (Smith and Skok 2007). Congress and the states did not anticipate the rapid growth in passenger car and truck traffic that would ensue during the 1960s and 1970s. While the country's population grew by 30 percent between 1956 and 1975, total vehicle-miles traveled (VMT) grew by 120 percent.[3] By 1975, 19 percent of the country's motor vehicle travel was on the Interstate System (FHWA 1975, Table VM-2). Truck travel had increased, and truck loads had grown to be much heavier than anticipated, largely because of changes in state weight limits, but also because of changes in federal policy. The 1956 act that created the Interstates included a single-axle truck weight limit of 18,000 pounds, a tandem-axle weight limit of 32,000 pounds, and a gross vehicle weight (GVW) limit of 73,280 pounds. While these limits were established as a condition for receipt of federal-aid funds, they were also accompanied by a grandfather provision that allowed states with higher weight limits to keep them. Responding to concern that state-to-state variability in weight limits created inefficiencies in the long-haul movement of freight, Congress in 1982 required all states to increase their minimum axle weight limits to 20,000 and 34,000 pounds for single- and tandem-axles, respectively.[4] Congress also raised the maximum GVW to 80,000 pounds.

Together, increased truck weights and traffic volumes greatly increased loadings on Interstate pavements. This increase is displayed for the country's rural Interstates in Figure 3-2 for the period 1970 to 2014. Pavements were deteriorating more rapidly than projected, and states were being pressed to spread their resources across worn segments, favoring faster and less expensive pavement overlays as opposed to more expensive, disruptive, and time-consuming full reconstruction.

Box 3-1 summarizes trends in the condition of Interstate pavements as reported in the U.S. Department of Transportation's (U.S. DOT's) biennial *Conditions and Performance* (*C&P*) report (FHWA 2016c). As noted, standard indicators of pavement condition, consisting of measures of surface

[3] Travel statistics in this paragraph are from FHWA (1995, Table VM-201).
[4] Surface Transportation Assistance Act of 1982 (Public Law 97-424).

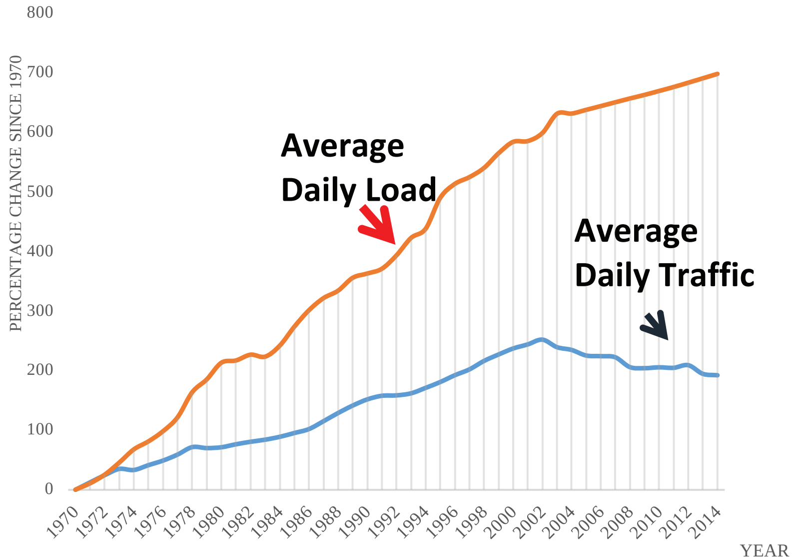

FIGURE 3-2 Percentage change in daily traffic volumes and loadings, rural Interstates, 1970–2014.
NOTE: In this chart, load refers to equivalent single-axle load. Average daily load refers to trucks only, and average daily traffic refers to all vehicles.
SOURCE: FHWA 2014a, Table TC-202C.

roughness or smoothness, suggest that states have been improving the condition of their Interstate pavement overlays in recent years by judiciously targeting their resurfacing and partial reconstruction work.[5] Underlying structural conditions, however, are not generally revealed by measures of surface smoothness and roughness. Studies of highway life-cycle costs that have investigated the practice of repeated pavement resurfacing to regain smoothness have confirmed that it produces diminishing returns over time—that is, shorter periods of serviceability between successive overlays. These studies have confirmed that this practice can produce higher life-cycle costs than an approach employing full-depth pavement reconstruction that is timed to reduce the frequency and total number of pavement repairs and overlays.[6]

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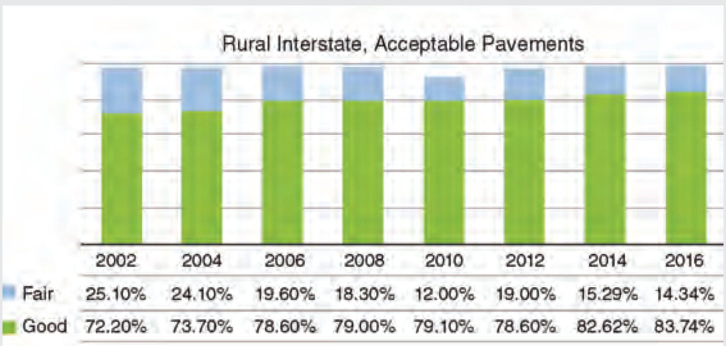
[5] Focused on reconstruction of the pavement surface layers, but not its full depth.

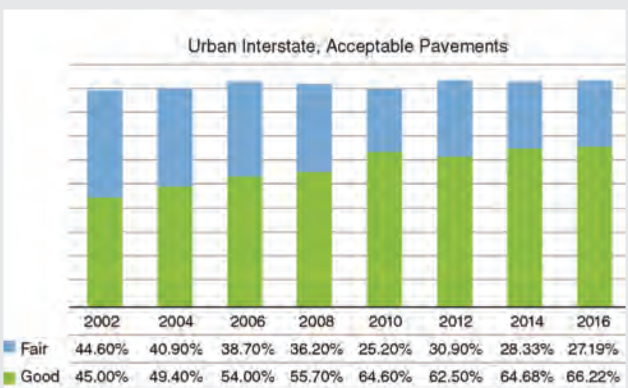
[6] Arizona DOT's "Evaluation of the Cost Benefits of Continuous Pavement Preservation Design Strategies Versus Reconstruction" (Smith et al. 2005) showed that reconstruction becomes as cost-effective as continuous preservation (e.g., using thin overlays, micro-surfacing, or other surfacing techniques) after two to three cycles of rehabilitation.

BOX 3-1
Determining Interstate Pavement Condition Using Surface Condition as a Proxy

The standard measure of the surface condition of pavements is the International Roughness Index (IRI), which measures cumulative vertical deflections in the pavement in inches per mile. The 2015 *Conditions and Performance* (*C&P*) report (FHWA 2016c) recognizes three categories of pavement quality: good, fair, and poor. Mileage rated good or fair is characterized as "acceptable." As the charts summarizing these ratings show, the mileage receiving acceptable ratings has been increasing over the past two decades for both rural and urban Interstates. However, urban Interstates have a larger percentage of mileage rated as in poor condition. Ratings based on surface condition measures, moreover, do not reveal the underlying condition of pavements (i.e., including substructure) and may merely reflect state spending that is being programmed largely for surface treatments.



(a)



(b)

SOURCE: FHWA 2017a, Table HM-47A.

The design life for Interstate pavements constructed in the 1950s and 1960s was 20 years. The fact that many of these pavements are still in service 50 to 60 years later under much higher traffic loadings and volumes than projected suggests that design and construction procedures from that era were more robust than the design records indicate (Mahoney et al. 2007, 90). Nevertheless, even if one assumes that a pavement structure can last as long as 50 years before requiring full reconstruction, this would imply that the older Interstate pavements are already in need of replacement, and that even the newest segments, constructed in the 1980s and 1990s, will have to be rebuilt over the next 20 years. If the entire 49,000-mile system had to be rebuilt over this period, starting with pavements that are 50 to 60 years old, this would mean that an average of more than 2,400 miles would have to be rebuilt each year.

While a national inventory of Interstate highway reconstruction plans is not available, there are indications that states are recognizing the need to schedule major reconstruction work on their portions of the Interstate System. Information from Pennsylvania DOT reveals that about 15 percent (~400 miles) of its Interstates were constructed or reconstructed from 1999 to 2018.[7] Michigan DOT has scheduled 9 percent of its Interstate miles for reconstruction between 2015 and 2023.[8] Other states, such as Iowa (I-80), are planning major reconstruction of portions of their Interstate System (IOWA DOT 2016). One of the case studies in Appendix I—of I-8 in Imperial County, California—describes a project to replace nearly 50 miles of deteriorated Interstate pavement surface and foundation with continuously reinforced concrete pavement that is expected to provide a substantially longer service period of up to 70 years. This segment of I-8 is a heavily used mixed urban and rural corridor where traffic disruptions would adversely impact both interurban and freight flows. Accordingly, California decided to construct a long-lived pavement structure that would minimize the need for future reconstruction interventions. California has also been implementing reconstruction projects in urban corridors. In 1998, for example, it implemented the Long-Life Rehabilitation Strategies Program to rebuild aging urban highway pavement structures with less cost to the traveling public. A 2004 reconstruction of I-15 in Devore is an example project from the program (Caltrans n.d.). The Devore project involved the reconstruction of 2.8 miles of badly damaged pavements in fewer than 20 days, whereas traditional methods would have required a 10-month road closure.

Just as Interstate pavements have aged and sustained higher traffic loadings than anticipated, so, too, have the system's many bridges. Today more than one-third of the more than 57,000 Interstate bridges have been in service for more than 50 years (see Figure 3-3). Generally, in contrast

[7] Personal communication with Pennsylvania DOT staff.
[8] Personal communication with Michigan DOT staff.

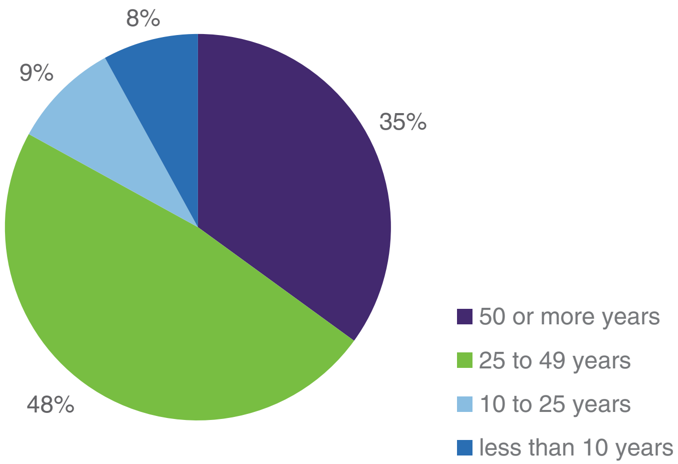


FIGURE 3-3 Percentage of the 57,000 Interstate bridges by age (years), 2017.
SOURCE: FHWA 2017d.

with pavements, the long-term deferral of major repair work can have catastrophic effects on bridges. States have therefore been required to pay close attention to their Interstate bridges as they age and sustain damage from usage or natural phenomena. About 3 percent of Interstate bridges received a poor rating in the 2015 *C&P* report (based on 2012 data) (FHWA 2016c), with a slightly higher percentage among bridges on the urban system (see Figure 3-4). Bridges receiving a poor rating are seldom unsafe and are almost always the target of state investments to address their deficiencies. The need to keep Interstate bridges in good condition, however, is relevant to the challenge states face in rebuilding their Intestate pavements. As states make investments to maintain the integrity of their aging Interstate bridges, they also need to ensure that their pavements remain serviceable through investments in both reconstruction and surface repairs.

Because so many of the Interstate System's original pavement foundations have not been replaced and are past due for reconstruction, a substantial reinvestment for this purpose is necessary. As discussed in the next chapter, uncertainties remain about how complicated and costly this work will be, particularly if growth in traffic accelerates deterioration and adds to the disruption entailed in highway repairs. Urban Interstates are particularly demanding with respect to major reconstruction; however, they are also most likely to experience future growth in Interstate traffic that will exacerbate pavement reconstruction needs.

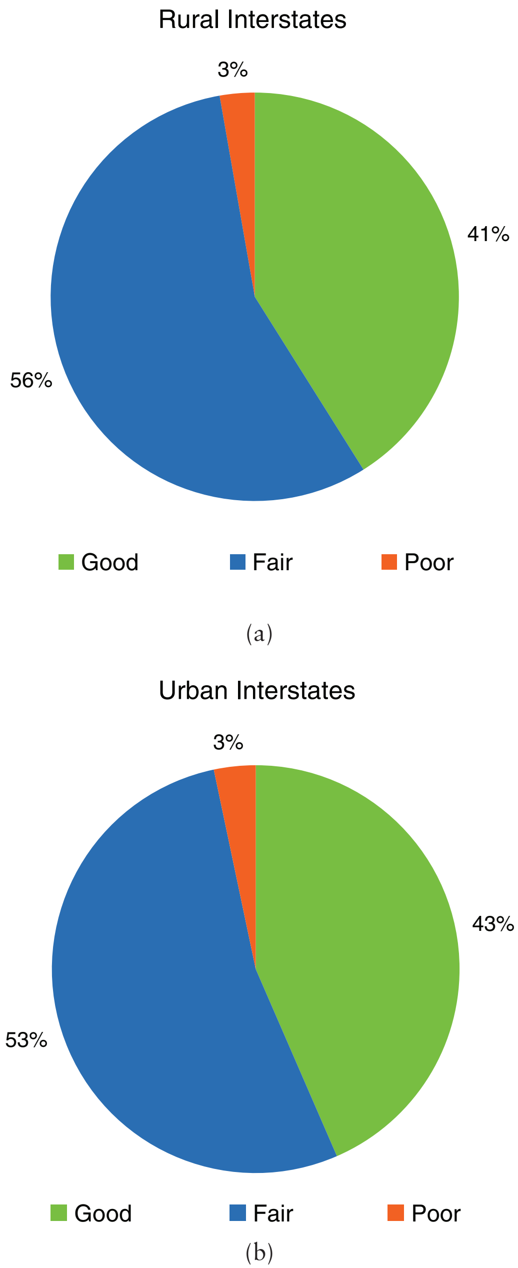


FIGURE 3-4 Share of (a) approximately 25,000 rural and (b) 32,000 urban Interstate bridges by condition rating, 2017.
NOTE: Because of rounding, data may not sum to 100 percent.
SOURCE: FHWA 2017d.

EXPANDING AND MANAGING URBAN SYSTEM CAPACITY

At a Glance

- Between 1980 and 2015, vehicle-miles traveled on the Interstate Highway System grew by more than 160 percent (compared with a 90 percent increase on all other public roads), while total lane-miles on the system grew by only 25 percent.
- Urban lane-miles increased by 115 percent from 1980 to 2015, while travel on these highways increased by more than 230 percent, and large metropolitan areas are forecast to experience most of the country's population and economic growth.
- The trucking industry estimates that congestion on the Interstate System, largely in urban areas, added more than $9 billion to operating costs in 2013.
- Urban highway congestion is a particularly complex issue, and alleviating it through physical means, such as lane additions, is an expensive and often impracticable option.

Growing Congestion

With the Interstate Highway System having reached 92 percent of its current length (in center-line miles) and 82 percent of its current lane-miles more than 35 years ago, the system's capacity has demonstrably not kept pace with user demand. Between 1980 and 2015, VMT on the Interstate System grew by more than 160 percent, compared with a 90 percent increase on all other public roads (see Figure 3-5). During this 35-year period of sharp growth in user demand, the total lane-miles on the Interstate System grew by only 25 percent (FHWA 2016b, Table HM-260; 2017c, Table HM-220).

Keeping pace with user demand has been especially challenging in urban areas. Lane-miles on the urban Interstate System increased by 115 percent from 1980 to 2015. Over the same period, travel on the system increased by more than 230 percent[9] as the country's urban population grew by more than half, compared with near-zero growth in rural population (U.S. Census Bureau 2016). Although the United States is geographically vast, its population has been concentrating in a relatively small number of large metropolitan areas. Today more than 250 million people out of the nation's 325 million total population live in metropolitan regions, and the

[9] Part of the reason for the growth in urban lane-miles and VMT is that some system segments (about 4,000 miles) that were previously designated as rural have been redesignated as urban as the country's metropolitan regions grew in population and land area.

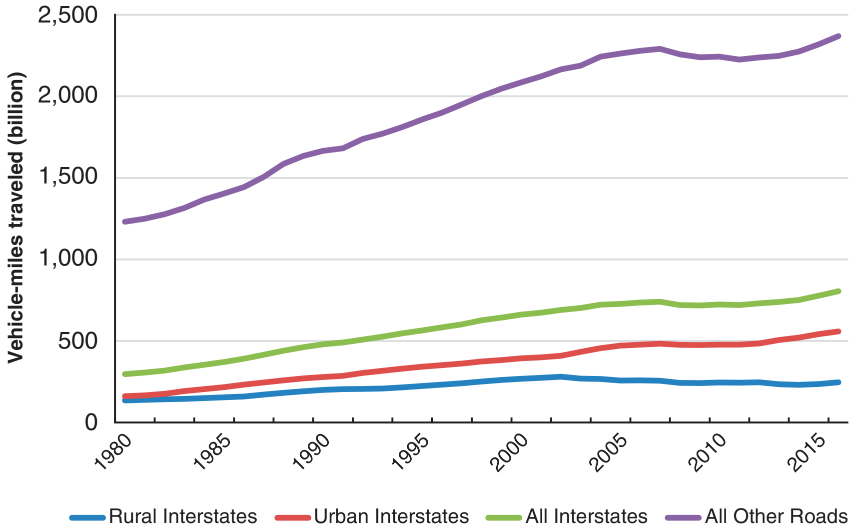


FIGURE 3-5 Growth in vehicle-miles traveled on Interstate highways and all other public roads, 1980–2015.
SOURCE: FHWA 2016a, Table VM-202.

largest 75 regions—each having more than 500,000 people—account for about half the U.S. population (Frey 2016).

The Interstates themselves have contributed to the country's metropolitan growth, making the system increasingly vital to commuting and other local and intraurban travel. In 1980 the urban Interstate System accounted for about 19 percent of all urban VMT; in 2015, it accounted for 25 percent (FHWA 2016a, Table VM-202). Moreover, the Interstates have contributed to the growth of "megaregions," as long stretches of the Interstate System now have a high proportion of urban miles that connect multiple metropolitan regions, such as in the Northeast Corridor (Portland, Maine, to Richmond, Virginia), Texas Triangle (Dallas, Houston, San Antonio), and Southern California (Los Angeles to San Diego counties) conurbations (Georgia Tech Research Cooperation 2008).

During periods of heavy local demand, large portions of the urban Interstate System, both within and outside central cities, fail to accommodate the demand of local as well as interregional and longer-distance travelers. Recurrent episodic congestion resulting from crashes, construction activity, and weather events produces chronic problems on many segments of the urban system during both commuting and noncommuting periods. Researchers at the Texas A&M Transportation Institute (TTI) and INRIX found that, in 2014, one in four urban highway trips were subject to delays from congestion and that drivers spent an average of 30 percent more time in their vehicles when traveling during congested compared with noncongested periods (Schrank et al. 2015, 8, 10). Although the TTI–INRIX data cover all urban highway trips, the large portion (25 percent) of urban VMT that occurs on the Interstates suggests that these highways are the site of much of this costly delay.

Trucks traveling on Interstates when hauling freight long distances are particularly affected by recurrent congestion on urban segments (BTS 2017). Average truck speeds on urban Interstates in some of the country's largest metropolitan areas (and over much of the 600-mile I-95 corridor between Richmond, Virginia, and the Massachusetts–New Hampshire border) are less than 45 mph (see Figure 3-6). Federal Highway Administration (FHWA) data indicate that 49 of the top 50 truck bottlenecks in the country are located at Interstate interchanges in metropolitan areas (ATRI 2017). The trucking industry—which is the largest component of the multimodal freight system in the United States, accounting for 65 percent of shipment value—estimates that congestion on the Interstate System added more than $9 billion to its operational costs in 2013 (ATRI 2014).

Urban freeway congestion is a complex issue, and alleviating it through physical means, such as lane additions, is an expensive and sometimes impracticable option when system right-of-way is constrained by land availability. Even if land can be acquired or existing right-of-way can be used more intensively, urban areas are expensive construction environments, and proposals for capacity expansion are often met with concern and outright opposition because of environmental and community impacts (Polzin [see Appendix C]). Some opponents believe that adding more urban freeway capacity will further contribute to the outward expansion of metropolitan areas, increasing public demand for still more roads and infrastructure (Milam et al. 2017; TRB 1995). Some also contend that expanding capacity by widening existing routes or building new lanes induces additional travel, leading to increased highway VMT adding to congestion over time, as well GHG emissions (Handy and Boarnet 2014). Capacity expansion plans, therefore, may be pursued through a combination of physical expansion and efforts to manage demand.

Managing Demand with Operations and Mobility Enhancements

Several case studies conducted for this report (see Table 3-1 and Appendix I) illustrate the limited ability to expand congested urban Interstates and the need to couple any possible capacity additions with demand management. Operational strategies to manage demand include variable speed limits, lane control signals, and dynamic conversion of paved shoulders to travel lanes. Corridor-level mobility management programs also coordinate the operation

FIGURE 3-6 Average truck speeds on Interstates in 2014.
NOTE: Speed and travel-time reliability were measured for more than 500,000 trucks on 25 freight-significant corridors on an annual basis (BTS 2015).
SOURCE: BTS 2015.

of parallel roads and area transit services to reduce corridor congestion and increase overall throughput (U.S. DOT n.d.). On I-25 in Denver and on I-15 in San Diego, for example, the highway agencies and metropolitan planning organizations (MPOs) opted for operational strategies that manage capacity and demand to produce more efficient traffic flows.

U.S. DOT is providing guidance to highway agencies interested in implementing integrated, corridor-level mobility management programs. These mobility management programs coordinate the operation of parallel roads and area transit services to reduce corridor congestion and increase overall throughput (U.S. DOT n.d.). Federally supported research has led to advances in tools for transportation system management and operations that promise even more effective corridor management in the future (see, for example, FHWA n.d.-b). Virginia DOT has implemented many of the active traffic management (ATM) features noted above on I-66 outside Washington, DC, in 2015. Previously, this corridor already had time-of-day (during peak periods) hard shoulder running in place, and thus the new ATM was aimed at improving off-peak performance. Its planner estimates that travel times on the corridor have decreased by 4 to 10 percent during

TABLE 3-1 Selected Case Studies of Projects Involving Urban Corridors and Interurban Freight Corridors

Projects/Plans	Improvement Types
Smart I-25 Managed Motorways, Denver, Colorado	Intelligent transportation systems
I-15 Integrated Corridor Management, San Diego, California	Integrated corridor management, intelligent transportation systems
I-66 Outside Beltway, Northern Virginia	Managed lanes, enhanced travel mode choices (bus and rail transit integration, park-and-ride lots), shoulder use, reconstruction of roadways and interchanges
I-405 Seattle, Washington	Managed lanes, high-occupancy vehicle (HOV) lane conversion, interchange enhancements, peak-period shoulder use, enhanced bus and bus rapid transit (BRT) service
I-80 and I-29, Council Bluffs, Iowa	Lane additions and interchange improvements to construct three express lanes for I-80 traffic and two local lanes for I-80/I-29 traffic
I-590 Winton Interchange, Rochester, New York	Interchange reconstruction to diverging diamond* to improve level of service
I-85 Kia Boulevard Interchange, West Point, Troup County, Georgia	New interchange to improve access to a manufacturing facility, accelerated bridge construction

*Diverging diamond is a type of interchange that eliminates the need for leftturning vehicles to cross the paths of incoming vehicles
SOURCE: FHWA 2014b.

off-peak periods and that delay-causing crashes have declined by more than 25 percent.[10] Recently, Connecticut DOT started a bus rapid transit line that runs along I-84 as a means of reducing congestion on the general-purpose lanes (TRB 2016). This example, like the Northern Virginia and Seattle cases in Table 3-1, demonstrates that the Interstate System interconnects with local transportation networks and can serve both low-occupancy automobiles and high-occupancy buses.

Managing Demand with Pricing

Highly congested metropolitan regions are starting to implement congestion pricing on their Interstates (see Box 3-2). However, while the imposition of tolls is allowed on some portions of the Interstate System, including

[10] Information in this section relevant to Virginia is based on material presented to the committee by Michael Fontaine (Virginia DOT) in July 2017.

BOX 3-2
Congestion Pricing

The concept of charging tolls that vary with roadway congestion levels has a long lineage, but its application on U.S. highways is fairly recent (TRB 1994). In brief, charging a fee for use of roads during congested periods allocates available supply with demand in the most economically efficient way. Shortages occur whenever a valued commodity or service has more demand than supply. For industries with high fixed or capital costs, expanding supply often cannot be accomplished in the short run. In the interim, prices rise until supply and demand equilibrate. Goods and services are allocated throughout the U.S. economy using prices to match demand with supply.

Variations on congestion pricing, also referred to as value pricing or managed lanes, have been applied on U.S. highways for almost two decades, including on several urban Interstates, with positive results (FHWA n.d.-d). Drivers who pay the toll save time and the revenues earned are available to improve capacity. Drivers faced with fees imposed during congested periods have choices beyond paying the fee, including changing the timing of trips to travel at less congestion times, traveling on routes without fees, sharing rides, or switching to transit. On the Interstates, only new added lanes can be tolled, which means that motorists always have the choice to travel in the unpriced lanes. Equity concerns are typically addressed by exempting vehicles with two or three occupants and transit vehicles from the congestion toll and by using the revenues gained to pay for the expanded capacity and additional transit services in the corridor. In the case of Interstate highways in urbanized areas, land constraints, capital costs, environmental concerns, and community opposition limit the amount of capacity that can be added. Charging fees during congested periods provides an effective and efficient mechanism for allocating available demand.

some special purpose lanes and highways that were tolled turnpikes before the system was created in 1956, it is prohibited on the large majority of Interstates constructed with federal aid thereafter. This management tool is therefore not available to mitigate congestion on most general-purpose Interstate lane-miles.[11] Pricing is limited to deployments on existing high-occupancy vehicle (HOV) lanes and newly constructed lanes that are paid for without federal aid by states and localities, sometimes in partnership with private investors. California has about 250 miles of high-occupancy toll (HOT) lanes in operation and 58 miles of these lanes under construction. Virginia recently opened HOT lanes on I-95 and I-495 outside Washington, DC, and on I-66 inside the I-495 Beltway. The state also plans

[11] General-purpose or general-use lanes refer to all lanes that are not express lanes, tolled, high-occupancy vehicle (HOV) lanes, or high-occupancy tolled (HOT) lanes.

to add variable-toll facilities on I-66 outside the Beltway and on I-64 in Hampton Roads.

Two planned HOT-lane projects—I-66 outside the Beltway in Northern Virginia and the I-405 express toll lanes in Seattle—are analyzed as case studies in this report (see Table 3-1 and Appendix I). The combined use of the general-purpose and toll-managed lanes is projected to increase vehicle throughput in the two corridors by 33 percent and 73 percent, respectively. In the case of I-66, the managed lanes are expected to attract some travelers who previously used the general-purpose lanes through the provision of toll-free incentives for HOV and bus transit options; accordingly, the corridor is projected to carry 43 percent more travelers relative to the current corridor configuration.[12] Similarly, the creation of the new managed lanes along I-820 and I-635 in Texas resulted in an increase of traffic throughput along those corridors.[13] By 2016, for example, the general-purpose lanes along the I-820 were carrying between 7 and 10 percent more vehicles than before the managed lanes were constructed. Even with those increases, the average speed in the general-purpose lanes increased between 10 and 15 percent. Whereas free-flowing traffic was guaranteed in the managed lanes, congestion in the general-purpose lanes was also reduced by 60 to 70 percent.[14] Benefits for passengers in the general-purpose lanes, however, may be temporary as demand continues to grow.

The demand for additional physical capacity and for more active and innovative management of new and existing capacity is almost certain to grow as metropolitan areas continue to experience most of the country's population and economic growth. As discussed in the next chapter, there is uncertainty about how this anticipated growth will translate to higher passenger car and truck traffic volumes. However, this uncertainty centers on the magnitude of the volume increases, not their location, which is expected to be mainly on the urban system. The case studies discussed herein indicate that while large metropolitan regions may continue to pursue the option of constructing new tolled facilities, physical constraints on right-of-way could eventually limit the applicability of this option. Moreover, in large metropolitan regions with widespread system congestion, it may become necessary to implement pricing on Interstates more extensively to incentivize the use of alternative routes and transportation modes and to shift more traffic to off-peak times. Indeed, as discussed in one of the case studies in Appendix I, planning is under way in the San Francisco Bay area to develop

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[12] Information in this section relevant to Virginia is based on material presented to the committee by Michael Fontaine (Virginia DOT) on July 2017.

[13] Information in this section relevant to NTE TEXPRESS and LBJ TEXPRESS is based on material presented to the committee by Belen Marcos on February 2017.

[14] Defined by operator as speeds below 50 miles per hour.

a 550-mile network of toll-managed lanes (Interstate and non-Interstate). The Metropolitan Transportation Commission (MTC) will operate 270 miles of the 550-mile network through conversion of 150 miles of existing carpool lanes and the addition of 120 miles of new lanes.

DEMAND FOR CHANGING THE SYSTEM'S LENGTH AND LAYOUT

At a Glance

- New travel demand arising from economic and population growth in certain areas may warrant changes to the Interstate Highway System's overall length and scope of coverage.
- Today, as a result of southern and westward development, more than 37 urbanized areas with populations exceeding 50,000 lack nearby access to Interstate highways.
- Ensuring that the Interstate System is responsive to changing user demands will require making choices, particularly regarding the envisioned role of the system for such purposes as international trade; inter- and intraregional traffic; and local, regional, and national economic development.

As discussed in Chapter 2, one of the principal planning criteria for the original Interstate Highway System was to connect most U.S. cities with 50,000 or more people (Eisenhower 1955). When the system was being planned in the 1940s and 1950s, waterways and railroads were the primary transportation connectors for the country's population and economic centers. Indeed, a comparison of the Interstate map developed in the 1940s and 1950s with a map of the country's major railroad trunk lines during the 19th and 20th centuries reveals considerable overlap.

Since its advent, however, the Interstate System has both reinforced this earlier pattern of U.S. development and helped realign it toward increasingly urban western and southern states. Many of these "Sun Belt" cities have experienced their greatest population and commercial growth since the development of the Interstate System. Some southern and western cities that were not connected to the Interstate System, being relatively small population centers such as Las Vegas and Phoenix, are now some of the country's largest and fastest-growing metropolitan complexes. Located far from navigable waters and railroad hubs, they emerged and developed almost entirely after the introduction of the automobile and the Interstate Highway System (TRB 2016).

Although the development of the Sun Belt was in its infancy in the middle of the 20th century, it would have been difficult for the original Interstate System planners to have imagined its speed and scale. Figure 3-7 shows the areas of the country, largely in the South and West, that have experienced the largest population gains over the past three decades (Sieber and Weisbrod [see Appendix D]). Because of this uneven development, in 2017 more than 40 urbanized areas with populations exceeding 50,000 did not have an Interstate highway within 25 miles (see Table 3-2).[15] Nearly half of these cities were in California and Texas, and most of the remainder were in other states of the South and West.

The scope of the Interstate System is not static, although an argument can be made that its extensions have been added in a mostly piecemeal fashion without strategic guidance. As of late 2018, FHWA's most recent records show that some of the cities listed in Table 3-2 are now being

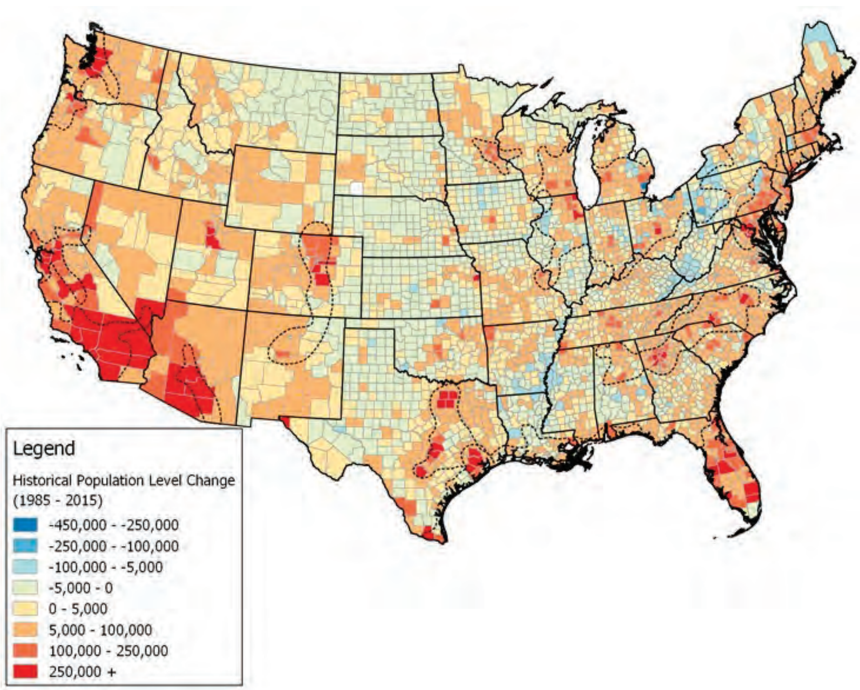

FIGURE 3-7 Population growth by county, 1985–2015 (dashed lines delineate existing and emerging megaregions).
SOURCE: Sieber and Weisbrod (see Appendix D).

[15] The 25-mile distance is measured from the Census-defined boundary of the urbanized area to the nearest Interstate route.

TABLE 3-2 Urbanized Areas (>50,000 population) Farther Than 25 Miles from an Interstate Highway in 2017

City	Population
McAllen, TX*	728,825
Fresno, CA	654,628
Oxnard, CA	367,260
Santa Rosa, CA	308,231
Atlantic City, NJ	248,402
Visalia, CA	219,454
Brownsville, TX*	217,585
Myrtle Beach–Socastee, SC–NC	215,304
Santa Barbara, CA	195,861
Salinas, CA	184,809
College Station–Bryan, TX	171,345
Panama City, FL	143,280
Merced, CA	136,969
Harlingen, TX*	135,663
Santa Maria, CA	130,447
Greenville, NC	117,798
Seaside–Monterey, CA	114,237
Salisbury, MD–DE	98,081
San Angelo, TX*	92,984
Bend, OR	83,794
Madera, CA	78,413
Florence, AL	77,074
Lake Jackson–Angleton, TX	74,830
Oshkosh, WI*	74,495
Porterville, CA	70,272
Dothan, AL	68,781
Dubuque, IA–IL	67,818
Jonesboro, AR*	65,419
El Paso de Robles (Paso Robles)–Atascadero, CA	65,088
Victoria, TX	63,683
Kokomo, IN	62,182
Sherman, TX	61,900
Sebring–Avon Park, FL	61,625
San Luis Obispo, CA	59,219
Lexington Park–California–Chesapeake Ranch Estates, MD	58,875
Mankato, MN	57,584
Kahului, HI	55,934
Fond du Lac, WI*	54,901
Farmington, NM	53,049
Arroyo Grande–Grover Beach, CA	52,000
Lewiston, ID–WA	51,924
Lompoc, CA	51,509
Villas, NJ	51,291
New Bern, NC	50,503

*By late 2018 these urbanized areas are located within 25 miles of an Interstate highway.

connected to the Interstate System (FHWA n.d.-c). For example, the addition of I-41 in Wisconsin connected Oshkosh and Fond du Lac, while the addition of I-555 in Arkansas connected Jonesboro. In south Texas, new Interstate construction along the emerging I-69 trade corridor will fully connect three more unserved cities, Brownsville, Harlingen, and McAllen.

Although thousands of miles of other, often high-quality, highways (largely on the 225,000-mile National Highway System) also help connect the country's population centers, the lack of access to the Interstate System is viewed by some of these smaller and emerging cities listed in Table 3-2 as detrimental to their growth and development. Of particular concern is that the Interstate System comprises the country's main trucking corridors, and their users depend increasingly on finely tuned logistics systems that manage freight flows precisely. The Interstate System's role in spawning and shaping the economic growth of newly emerging cities after World War II is not lost on communities that are now challenging the rationale for the system's being treated as "complete" when the country it serves is dynamic and changing.

In addition to connecting the country's population centers for personal travel, the original planners of the Interstate System sought to improve its long-distance freight corridors. The extent to which this planning took into account the freight demands of international trade is unclear, but it was probably minimal given that the annual value of imported and exported goods did not even surpass $50 billion (9.2 percent of gross national product [GNP] in 1960) until after 1960 (Bureau of Economic Analysis 2018; The World Bank n.d.). Nevertheless, the system's original plan containing multiple east–west routes was farsighted. It strengthened the position of several West Coast ports (e.g., Long Beach–Los Angeles, Oakland, Seattle, and Tacoma) as they competed for the escalating trade with Japan, Korea, China, and other Pacific Rim countries commencing in the 1960s. It was not until 1979, however, that the final section of the north–south I-5 was completed to form the first continuous north–south freeway connecting with both Canada and Mexico, which would soon become the United States' largest trading partners.

By the time the I-5 corridor was completed, the value of international trade had grown to nearly 5 times that in 1960 when adjusted for inflation (U.S. Census Bureau 2018), and trade with Canada and Mexico was leading the way. The Canada–U.S. Free Trade Agreement in 1987 and the North American Free Trade Agreement (NAFTA) that included Mexico in 1994 reinforced and then escalated this north–south pattern. Today, Canada and Mexico collectively account for nearly 25 percent of the value of U.S. international trade (U.S. Census Bureau 2017).

Even before passage of NAFTA, Congress in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 identified 14 potential future freight corridors—known as the Congressional High-Priority Corridors—whose highways would be upgraded and designated as part of the Interstate System. The CANAMEX Trade Corridor was prescribed to create an Interstate route parallel to I-5 farther to the east (I-15 spanning from San Diego County, California, to Alberta, Canada). While I-15 has been completed, another north–south trade corridor, I-69, is envisioned farther to the east, spanning from Sarnia, Ontario, Canada, to the Lower Rio Grande Valley in Texas. I-69's development from myriad state highway routes has been delayed by many factors, including the lack of dedicated funding.

Keeping pace with the changing levels and patterns of international trade is of course only one source of demand for changes to the length and layout of the Interstate Highway System. Congress has amended its list of high-priority Interstate corridors several times since 1991. As shown in Figure 3-8, the list now includes an east–west corridor from Virginia to Kansas and a north–south corridor from South Carolina to Michigan. In addition, the list includes some extensions that are intended to bridge system discontinuities

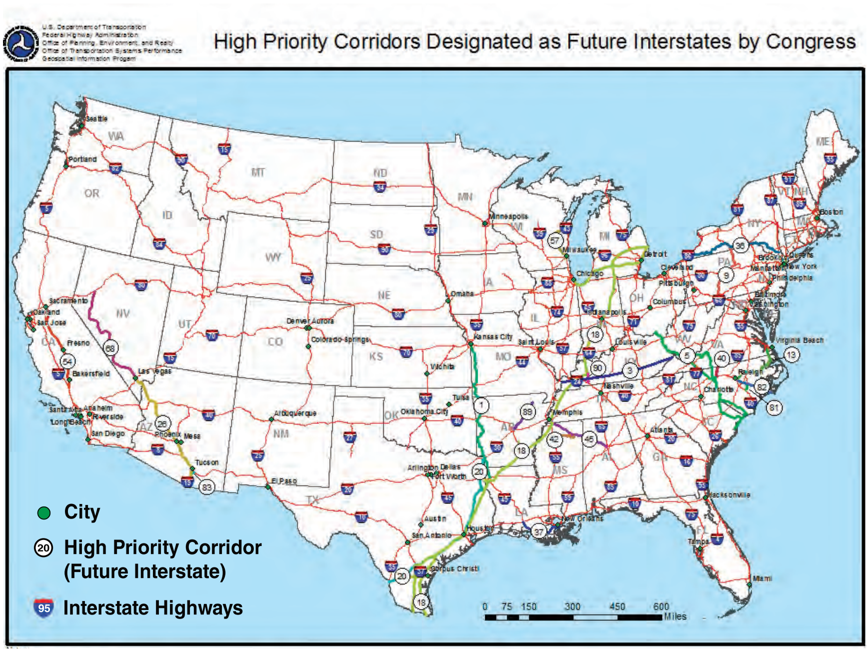

FIGURE 3-8 High-priority corridors designated as future interstates by Congress, 2017.

NOTES: Colors are added for clarity only. Corridor numbers correspond to statutory listing in Section 1105(c) of ISTEA 1991, as amended. Some portions of the future Interstate have been constructed to Interstate standards, open to traffic, and signed as Interstates. Corridors based on information available as of October 11, 2017.

SOURCE: FHWA n.d.-a.

within a single state or across two or three states. These additions are intended to serve such purposes as connecting the core cities of expanding megaregions (e.g., Raleigh–Norfolk corridor), providing farm-to-market access (Bakersfield to Sacramento), and supporting interregional and rural economic development (along the route from Memphis to Birmingham).

As explained in Chapter 2, under current law FHWA can at the request of a state or states designate sections of the 225,000-mile National Highway System to be absorbed into the Interstate Highway System, but this authority is not accompanied by additional federal funding for the needed upgrades. States must use existing sources of revenue that already are subject to competing demands elsewhere on their systems. The required investment can be substantial. A planned 8-mile upgrade of US-77 to become part of I-69 in Texas (see Appendix I) is projected to cost more than $9 million per mile. The upgrades would include geometric improvements, interchange additions, and pavement reconstructions, all intended to increase capacity and enhance safety.

The project to convert US-77 to I-69, which was designated a High-Priority Corridor, is expected to serve multiple purposes, including providing new connections for freight flows between the Rio Grande Valley and the Michigan–Canadian border. This would facilitate the multimodal integration of freight movements by truck, rail, air, and inland waterways at Memphis and improve the connectivity of communities in western Tennessee. The project is an example of the effort to ensure that the Interstate System meets changing demands for purposes ranging from facilitating international trade and interregional traffic flows to supporting local and regional economic development. However, it is also an example of how criteria have not been established for prioritizing these purposes, particularly to guide the allocation of federal aid.

ENSURING SAFETY WHILE ACCOMMODATING A GROWING AND CHANGING VEHICLE FLEET

At a Glance

- Although the Interstates are the country's safest highways, they account for more than 5,000 traffic deaths annually.
- Safety assurance will remain a challenge for highway agencies as advanced vehicles and systems affect traffic flows and require infrastructure accommodations.
- A critical factor in the safety assurance challenge will be to provide protection from cyberattacks.

Although they are the safest highways per unit distance of travel, U.S. DOT statistics show that more than 5,000 people, representing about 13 percent of total traffic deaths, died in motor vehicle crashes on Interstate highways in 2016 (see Figure 3-9). It has also been noted that Interstate truck traffic has grown much faster than originally forecast, and many of the deaths (21 percent) involve crashes with large trucks. Most of these deaths (72 percent)[16] occur in smaller, passenger vehicles that share the road with large trucks. Interstate pedestrian fatalities (472 of 674 in 2016) occur primarily on the urban system where highways cross densely populated areas.[17] These fatalities do not include those that occurred on other roads merging with Interstates at interchanges.

Despite the safe design of the Interstates relative to other highways, reducing the number of crashes on the system clearly remains an important challenge. Interstates of the future will need to continue to adopt state-of-the-art safety practices to mitigate the risks arising from growth in traffic volumes and the higher travel speeds permitted. Moreover, changes to accommodate increased traffic demand will need to be accompanied by assessments of the likely safety impacts of those changes and the need to deploy countermeasures—for instance, under circumstances in which

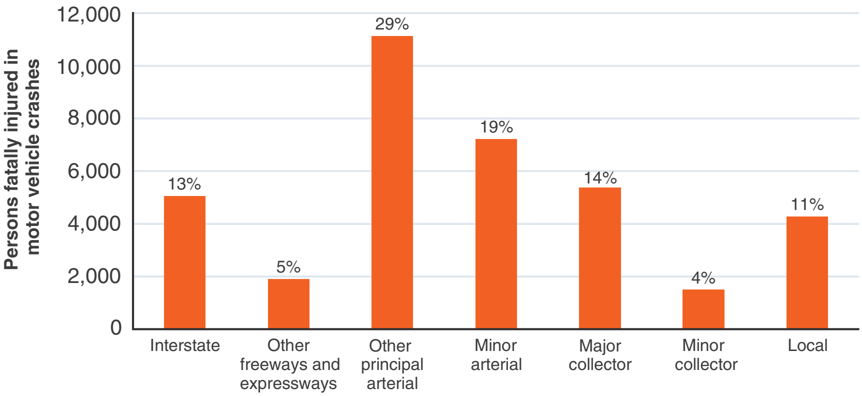

FIGURE 3-9 Persons fatally injured in motor vehicle crashes, by road classification and as percentage of year's total fatalities, 2016.
SOURCE: FHWA 2017b, Table FI-220.

[16] Analysis provided by the Insurance Institute for Highway Safety, based on data from the U.S. DOT's Fatality Analysis Reporting System (FARS).

[17] Analysis provided by the Insurance Institute for Highway Safety, based on data from FARS. Also, additional research has found a two-to-one ratio between pedestrian deaths on Interstates in urban and rural contexts from 1993 through 2012 (AAA Foundation for Traffic Safety 2014).

shoulders are repurposed as travel lanes or trucks are allowed to platoon using electronic systems.

Many new highway and vehicle technologies being developed and starting to be introduced have the potential to alter the operations and safety performance of the highway system, including Interstates. Many of these technologies are vehicle-centered, such as driving-assist features and automated vehicles, while others, such as real-time traffic analysis systems that regulate traffic control devices, have a strong infrastructure orientation. Still other technologies are aimed at integrating vehicles and highways through increased connectivity (i.e., vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I] communications).

Although these features are expected to improve safety and operability, their introduction also poses challenges. In particular, for them to achieve their promise, they will have to function reliably and safely. Designing these new systems to ensure that they are reliable and minimize their potential to introduce unintended safety hazards will be an ongoing challenge for automakers, their suppliers, and highway engineers. Safety assurance will become a special challenge for highway agencies, as advanced vehicles and systems will affect traffic flows, both on and off the Interstates, and likely will require infrastructure accommodations to support some of their capabilities. Although there has been much publicity about the future of automated vehicles, moreover, most vehicles on the road over the next two decades will continue to have human drivers. Mixed fleets of automated and human-operated vehicles will pose a particular challenge.

The safety assurance challenge will also demand protection from cyberattacks, as the advanced electronic, computer, and telecommunications systems of automated vehicles will have the capability to gather, analyze, and transmit large amounts of data that may present opportunities for such attacks by individuals as well as adversarial nations. To address this issue, the automotive industry is assessing cybersecurity risks associated with emerging technologies and working through collaborative organizations, such as the Automotive Information Share and Analysis Center (Auto-ISAC), to develop and share best practices for securing vehicle communications (Auto-ISAC 2018). Likewise, the National Highway Traffic Safety Administration (NHTSA) has been working with the National Institute of Standards and Technology (NIST), using NIST's Technology Cybersecurity Framework (NIST n.d.), to encourage the automotive industry to adopt practices that will improve the cybersecurity of vehicles (NHTSA n.d.). And while neither the existing highway design standards nor the Technology Cybersecurity Framework employed by NHTSA addresses the cybersecure deployment of infrastructure-related technologies, the prospect of connected vehicle technologies[18] on Interstates and other highways suggests the need for highway agencies to play a far more prominent role in such efforts.

The development of automated and connected vehicle technologies and their deployment on the Interstate Highway System is a complex topic involving many potential technologies, systems, and capabilities. The committee commissioned a paper (see Appendix F) to provide an overview of the state of technology; its progress; and assessments of how new technologies could impact Interstate highway operations over the next 10, 20, and 50 years. This assessment and related observations by the committee, discussed in the next chapter, suggest that the impacts could be far-reaching and extend over a time horizon that cannot be well defined at this point in time. The challenge for decision makers contemplating the future of the Interstate Highway System will be to ensure that the system is robust and adaptable, avoiding premature investments in assets or the introduction of standards that hinder or foreclose development pathways.

ADDING RESILIENCE

At a Glance

- The potential impacts of changing climate and extreme weather events on the Interstate Highway System are serious and multifold.
- Designing and retrofitting Interstate infrastructure to add resilience will involve costly undertakings that will require a strategic, risk-based approach.
- States need to identify the climate change impacts relevant to their system, how those impacts are likely to manifest, and which system segments are most vulnerable.

When much of the Interstate Highway System was being planned, designed, and built during the 1960s and 1970s, there was no understanding of the threat of GHG buildup and how a changing climate could adversely affect the transportation system and other critical infrastructure through such consequences as rising sea levels and extreme weather events. Individual portions of the Interstate System were designed and built for the typical range of weather and climate experienced regionally in the past. For

[18] Automated vehicle technologies relieve drivers of some, or perhaps all, of the tasks associated with controlling and navigating the vehicle. Connected vehicle technologies are devices installed in vehicles that exchange information with other devices within the same vehicle, other vehicles, or road infrastructure.

instance, environmental factors such as the expected duration and intensity of rainfall affected design choices about subsurfaces, materials, and drainage capacity, choices that usually accounted for environmental extremes experienced in the past, such as 100-year storms and floods.

The need to make the Interstate System and other transportation assets more resilient to the consequences of climate change is now widely recognized, in part because of recent experience and in part because of forecasts by much of the science community. Increases in very hot days, in the frequency and intensity of precipitation events, and in hurricane intensity, which are predicted effects of climate change, are now being observed.[19] In Alaska, for instance, the thawing permafrost is causing subsidence to roadbed and bridge supports. The city of Houston has experienced three 500-year storms since 2015, including Hurricane Harvey, which caused more than $125 billion in damage in 2017 (NOAA 2018). And in 2012, Superstorm Sandy severely affected New York City, the coast of New Jersey, and other points along the northeastern seaboard, causing more than $70 billion in damage. According to data from the National Oceanic and Atmospheric Administration, since 1980 the United States has sustained more than 200 weather and climate disasters in which damage, response, and cleanup cost exceeded $1 billion per event (see Figure 3-10). The total cost of these occurrences was more than $1 trillion. Every U.S. state was affected by one or more of these catastrophic events, which included major heat waves, severe storms, tornadoes, droughts, floods, hurricanes, and wildfires. Table 3-3 lists Interstate highways that were recently closed because of severe weather events.

The potential impacts of changing climate and extreme weather on the highway system are multifold. Pavements and bridges can be adversely affected not only by extreme changes but also by unexpected deviations from normal weather patterns, such as wetter winters and drier summers. The effects can be pernicious, including the erosion of road base and bridge supports from gradual land subsidence; softening, rutting, and buckling of pavement from excessive heat; and freeze–thaw cycles and thermal expansion that damage bridge and pavement joints and decks. Generally wetter conditions, for instance, can reduce the load capacity of pavement structure and require improved surface and subsurface drainage. The extreme effects of climate change can include damage from tidal storm surges and widespread flooding that inundate coastal highways (see example in Figure 3-11) and move floodwaters farther inland; fast-moving wildfires that damage and close highways for extended periods; and flash floods and mudslides

[19] An examination of the range of potential impacts to Interstate infrastructure can be found in *Special Report 290*: *Potential Impacts of Climate Change on U.S. Transportation* (TRB and NRC 2008). In particular, see Chapter 3, "Impacts of Climate Change on Transportation."

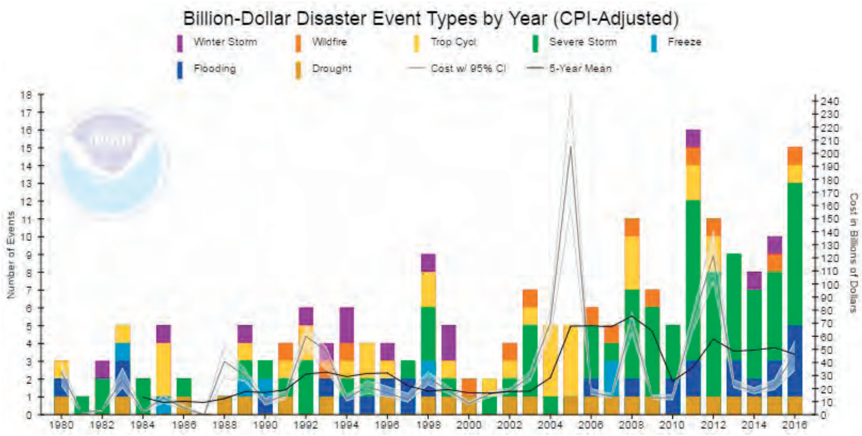

FIGURE 3-10 Increasing trend in number of severe-loss events in the United States due to natural catastrophes per year, by type of event, 1980–2016.
NOTE: "Cost with 95% CI" denotes 95 percent confidence interval estimates of cost uncertainty; "5-year mean" denotes the 5-year cost mean.
SOURCE: Wuebbles and Jacobs (see Appendix G).

TABLE 3-3 Interstate Highways Subjected to Closure because of Extreme Weather Events

Interstate Highway	Location	Weather Event	Year
I-10	New Orleans, Louisiana	Hurricanes Katrina and Rita	2005
I-110	Biloxi, Mississippi	Hurricanes Katrina and Rita	2005
I-24	Nashville, Tennessee	Flash flooding	2010
I-95	Connecticut, New Jersey, New York	Superstorm Sandy	2012
I-10	Desert Center, California	Flash flooding	2015
I-95	Fayetteville, North Carolina	Hurricane Florence	2018

SOURCES: Breslin 2018; Miller 2012; TRB and NRC 2008; Williams 2015.

FIGURE 3-11 Section of I-45 submerged from the effects of Hurricane Harvey during widespread flooding in Houston, Texas (August 27, 2017).
SOURCE: Reuters/Richard Carson.

that bury or wash out highways located in dry and drought-stricken regions. Moreover, when such damages occur, resultant disruptions to the operations of the Interstate Highway System can lead to even more serious outcomes by hindering emergency response and evacuation.

As discussed in the next chapter, the impacts of climate change are expected to vary by region, and there is uncertainty about how they will evolve over time. It is certain, however, that transportation agencies across the country will need to revise how they plan, design, construct, operate, and maintain their highways to account for the impacts. It will be necessary to develop and implement robust design and construction standards that assume greater frequency and severity of extreme events, especially for core facilities, such as Interstates, major bridges, and emergency access and evacuation routes. Agencies will also need to assess and decide where and where not to build new assets. These efforts will require research, testing, and innovation in such areas as materials (e.g., asphalt and concrete mix designs), design criteria, construction techniques, and maintenance practices. They will also require translation of available climate projections into guidance and engineering standards that practitioners can use when planning and designing future infrastructure projects (Stahl et al. 2016).

While some assets with relatively shorter design lives, such as pavements, will provide early opportunities for upgrading Interstate highways to add resilience, the cost of redesigning and retrofitting certain Interstate infrastructure—such as elevating a bridge or highway or relocating a right-of-way—will be costly undertakings that will require a strategic, risk-based approach to investment decisions. The Interstate System includes many long-lived assets that nominally will not be replaced or undergo major reconstruction for years. Furthermore, past choices about where to locate some routes (e.g., in vulnerable coastal and riverine settings) cannot be undone without massive financial investments and community disruption.

The challenge can be viewed broadly as a risk management "systems" problem that will require states to identify the climate change impacts (e.g., sea level rise, extreme precipitation events) most relevant to their particular system, how those impacts are likely to manifest themselves (e.g., inundation from storm surge), and which system segments are most vulnerable and present the greatest risk if action is not taken or is delayed. The choices are likely to require that future professionals be trained in adaptive design and risk management.[20]

Strategies for incorporating future changes in the natural environment into infrastructure planning and design are now emerging, prompted in part by recent disasters. Examples are FHWA's 2014 release of Hydraulic Engineering Circular (HEC) 25, *Highways in the Coastal Environment: Assessing Extreme Events, Volume 2* (FHWA 2014c) and 2016 release of HEC 17, *Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience, 2nd Edition* (FHWA 2016d). These documents provide technical guidance and methodologies for incorporating climate change considerations, including sea level rise, storm surge and wave action, and extreme flood events, into the planning and design of highway projects in coastal and riverine environments. More tools of this type, along with quantitative measures and indicators of vulnerability and societal impacts, will be needed to inform resource allocation decisions by transportation agencies and to provide guidance for system planning, design, and operations and maintenance activities.

In this regard, states and FHWA can draw on experience garnered from such areas as seismic protection. Over the past 40 years, transportation agencies have been proactive in evaluating lessons learned from significant

[20] It is notable that the American Society of Civil Engineers' (ASCE's) Committee on Adaptation to a Changing Climate is developing a manual of practice on adaptive design and adaptive risk management. Adaptive design and risk management employ a methodology based on quantitative and probabilistic analysis of potential losses that support economic valuation and benefit-cost analysis of adaptive solutions based on real options. These adaptive solutions introduce the concept of exercising options to meet changes in the projected hazards in the future (NASEM 2018).

earthquakes, researching solutions, and implementing improved design and retrofit guidelines and standards for bridges and infrastructure. California, for instance, has long used a risk-based approach for analyzing earthquake vulnerabilities to determine priorities for highway bridge retrofitting and replacement. These efforts have enabled the state to make effective overall use of investments for earthquake protection, but the total investment has nevertheless been substantial. The resources that will be needed to make the Interstate System more resilient to climate change promise to be large, but the exact level of that investment is unclear at this point, and may remain so for some time.

SUMMARY

This chapter has described pressing and emerging challenges that lie ahead if expectations for the Interstate Highway System are to be met.

Commencing the enormous task of rebuilding the system's pavements before they become unserviceable over large segments of the system, while maintaining the system's aging bridges. Many of the Interstate pavements constructed in the 1950s and 1960s were designed for 20-year service lives but have now been in use more than 50 years without reconstruction of their base course and foundations, this despite much higher traffic loadings than projected. Even if one assumes that a pavement structure can last 50 years before requiring full reconstruction, the system's oldest segments are already long overdue for this work. Even most of the newest Interstate segments, built in the 1980s and 1990s, will need to be rebuilt over the next 20 years. As this work is being accomplished on roadways, states will continue to need substantial resources to also invest in replacing and maintaining the integrity of their aging Interstate bridges.

Meeting the growing demand for investments in physical capacity and active management of the urban system as metropolitan areas continue to experience most of the country's population and economic growth over the next few decades. Large portions of the Interstate System, especially in metropolitan areas, are already severely congested and unable to accommodate the demands of local, interregional, and longer-distance travelers. Alleviating the problem of urban freeway congestion through such physical means as lane additions is expensive and sometimes impracticable, particularly when system right-of-way is constrained by land availability. Even if land can be acquired or existing right-of-way can be used more intensively, urban areas are expensive construction environments, and proposals for capacity expansion are often met with concern or outright opposition because of community impacts.

Ensuring that the system remains adaptable to continued evolution of the country's population and economy. Although thousands of miles of high-quality highways other than Interstates connect the country's population centers, lack of access to the Interstate System may be viewed by some smaller communities and emerging cities as detrimental to their growth and development, particularly given that the system includes the country's main trucking corridors. The Interstate System was planned in the 1950s and considered complete in the 1990s despite a changing pattern of demand that is increasingly urban, western, and southern.

Improving the system's safety performance as traffic volumes increase and the system is modified to increase capacity and throughput. Although the Interstates are the nation's safest highways, they account for more than 5,000 traffic deaths annually. It will be necessary to continue to adopt state-of-the-art safety practices for the Interstates of the future to mitigate the additional risks arising from growth in traffic volume.

Ensuring that the system is robust and adaptable to changing vehicle technologies, which entails avoiding premature investments and the introduction of standards that hinder or foreclose development pathways. Many new technologies have the potential to alter the operations and safety performance of the nation's highway system, including the Interstates. Some of these technologies, such as driving-assist features and automated vehicles, are vehicle-centered, while others, such as real-time traffic analysis systems that inform traffic control devices, have a strong infrastructure orientation. Other technologies will involve connectivity of vehicles and infrastructure. Many of these technologies will have potential vulnerabilities that will require protection from exploitation by outsiders.

Developing strategies that address future climate conditions and incorporating them into infrastructure planning and design, starting with the development of robust standards that assume greater frequency and severity of extreme weather events. When much of the Interstate System was being planned, designed, and built during the 1960s and 1970s, there was limited knowledge of the threat of greenhouse gases and how a changing climate could adversely affect the transportation system. Consequences include rising sea levels and extreme weather-related events. Transportation agencies across the country will need to revise how they plan, design, construct, operate, and maintain their highways to account for these impacts.

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Abbreviations

AAA	American Automobile Association
ATRI	American Transportation Research Institute
Auto-ISAC	Automotive Information Sharing and Analysis Center
BTS	Bureau of Transportation Statistics

DOT	Department of Transportation
Caltrans	California DOT
FHWA	Federal Highway Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NYCEDC	New York City Economic Development Corporation
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation

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4

Confronting an Uncertain Future

The previous chapter identifies current and emerging challenges that face decision makers seeking to renew, rightsize, and modernize the Interstate Highway System. A number of these challenges have been recognized for some time, while others have attracted attention only recently. Described in Chapter 3 as they are understood today, the challenges may appear quite different in the future as user demands, technological capabilities, economic and environmental conditions, and other circumstances—including policy choices—change. This chapter reviews some of the likely areas of change that together contribute to a future that is uncertain, but with which decision makers will nonetheless have to contend as they make choices about where, when, and how much to invest in expensive and long-lived assets included in the Interstate Highway System.

As discussed in Chapter 1, the study committee commissioned five resource papers (see the appendixes) that consider how the future may evolve with regard to several developments likely to substantively impact the Interstate System:

- Chi (see Appendix E) examines how a changing U.S. population and its spatial patterns could affect demand for Interstate highways in different parts of the country.
- Sieber and Weisbrod (see Appendix D) consider how the scope of this demand could be affected by spatial and sectoral changes in the economy.
- After reviewing past influences on travel demand, Polzin (see Appendix C) discusses how the combination of changes in demographics,

economic activity, technology, and other factors—including the availability of alternatives to highway travel—could translate into differing rates of growth in motor vehicle travel demand in general and on the Interstate System specifically.

- Shladover (see Appendix F) considers how the development and deployment of connected and automated vehicle technology could affect both the supply and demand sides of transportation and the Interstate System.
- Wuebbles and Jacobs (see Appendix G) examine how climate change and its consequences could impact the Interstate System's condition, performance, and use.

These papers confirm that some developments, such as population growth rates and their spatial dimensions, can be forecast substantially better than others—especially technology change. In each case, however, uncertainties about the magnitude, direction, and nature of change complicate the prediction of future demand and supply for the Interstate System. This complexity is compounded by the interaction among such developments. As noted in the previous chapter, the original planners of the Interstate System failed to estimate how the system would be used and perform just two decades after it was approved by Congress. Although informed by fairly accurate forecasts of the U.S. population, planners in the 1950s had little insight into how important emerging demographic, economic, and policy changes—such as much larger numbers of women driving, marked growth in international trade, and large increases in allowable truck weights and truck traffic—would affect their predictions. Even today, transportation planners are adjusting their near-term travel forecasts to account for unanticipated changes in information and communication capabilities that have allowed more workers to telecommute; enabled online shopping with more home delivery of goods; and provided travelers with more informed, real-time modal and routing options.

The first section that follows presents a review of U.S. population forecasts, both for the country as whole and for geographic regions, down to the level of counties. Although county-level population forecasts involve greater uncertainty relative to those at higher levels, they provide insights into how the Interstate System's scope and its proximity to, and connections with, communities could change over the next 40 years. Perhaps more than any other future development, population growth and its spatial patterns can be assessed with a reasonable degree of confidence, and related to the Interstate System and demand for changes to its geographic coverage. Because demand will depend on more than the size and distribution of population, this section also considers how sectoral, compositional, and locational shifts in economic activity among regions could have implications for demand for access to the Interstate System.

As discussed in Chapter 3, between 1980 and 2015, vehicle-miles traveled (VMT) on the Interstate System grew by more than 160 percent, compared with a 90 percent increase on all other public roads. If both the U.S. population and the economy grow over the next several decades, as can be reasonably expected, growth in highway travel will almost certainly ensue, and the Interstate System as a whole will likely become more heavily used. While reasonable projections of the growth of the population and the economy can be made, they need to be accompanied by assumptions about the composition of this growth so it can be related to changes in highway demand. Whether the growing population is older or younger, living in smaller or larger households, and concentrated more or less in urban or rural areas all will affect demand. Likewise, a growing economy that is more or less goods- or service-oriented or that involves more or less trade will be accompanied by different patterns and levels of travel. The second section of the chapter therefore considers how future changes in the U.S. population and economy could interact with one another and with other factors related to travel behavior to affect growth in passenger and freight travel generally and on the Interstates specifically. These rates of growth will have implications for system capacity demands and for wear and deterioration of pavements and bridges, and because of the significant uncertainties involved, must be forecast within a range of confidence.

The third and fourth sections of the chapter consider developments in two key areas that are expected to have profound effects on the Interstate Highway System, but whose timing and nature cannot be forecast and assessed in the same manner as changes in population and the economy. The first of these areas is major technological changes, the most prominent of which is the prospect of large-scale deployment of connected and automated vehicles. The second key area is a dramatically changing climate and its environmental consequences, which could lead to major economic and social disruptions. Because both an increasingly automated transportation system and climate change are considered highly likely, contemplating a future Interstate Highway System without considering their potential impacts would be untenable. While the future changes in these areas cannot be assessed in detail, these two sections of the chapter review a range of possible outcomes that can inform near-term decision making.

CHANGING CENTERS OF POPULATION AND ECONOMIC ACTIVITY

At a Glance

- The historical trend of strong population growth in the West and South has continued into the present century. States in these regions can be expected to see increased demand for access to the Interstate System. Geographically uneven growth will exacerbate this pressure and the access disparities among regions.
- Projections point to some significantly growing counties that currently do not have access to an Interstate highway.

This section focuses on how forecast spatial and sectoral changes in the U.S. population and economy are likely to affect demand for modifications to the scope of the Interstate highway network. Decisions about where to extend the length of the Interstate System, or in some cases perhaps redesignating segments, will entail consideration of national- and network-level passenger and freight traffic flows.

Scope of the Interstate System and the Changing Geography of the U.S. Population

While the demand for access to the Interstate System is affected by factors other than adjacent population, travel demand is highly correlated with population. As shown in Table 4-1, the historical trend of strong population growth in the West and South has continued into this century, with these regions growing approximately four times as fast as the Northeast and Midwest. During this period, six states—Arizona, California, Florida, Georgia, North Carolina, and Texas—collectively accumulated more than 50 percent of the population growth nationwide. Given the increase in VMT on the Interstate highways in the past few decades compared with

TABLE 4-1 U.S. Population Change by Census Region

Census Region	Net Change 2000–2016 (%)
Northeast	4.9
Midwest	5.5
South	22.0
West	21.3
U.S. Total	14.8

SOURCE: U.S. Census Bureau 2016.

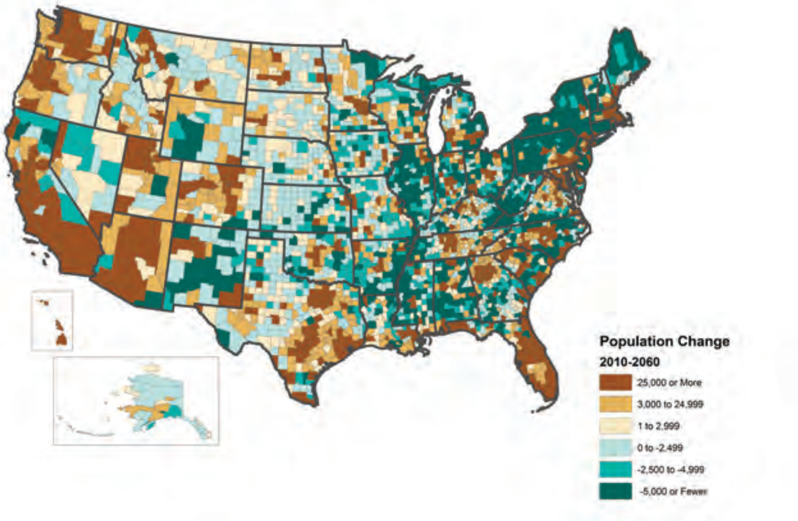
that on other roads, continued geographically uneven growth is likely to exacerbate disparities in Interstate access among regions.

The Census Bureau forecasts the U.S. population over multiple time frames and for various aspects of its composition (e.g., age, sex, race, and ethnicity). These forecasts can be used to develop county-level projections of demand for the Interstate System over the next 40 years as the size and density of the country's population change spatially. Figure 4-1 shows the population size and density by county as of 2010 and projected patterns of change by 2060. Based on the Census Bureau's midrange forecasts, total U.S. population will grow by 37 percent (from 310 million to 426 million) during this period, with population growth areas being concentrated in Arizona, California, Colorado, Florida, Hawaii, Oregon, southeast Texas, Utah, Washington, counties on the metropolitan east coast, and a triangular area between Atlanta, North Carolina, and Nashville. Remarkably, the number of counties, mostly rural, that are projected to experience a population decline is larger than the number of counties forecast to gain population. The former counties are principally in the northeast corner to the Appalachian region; bordering the Great Lakes, except Lake Michigan; along the Mississippi River; the Deep South states; and Alaska.

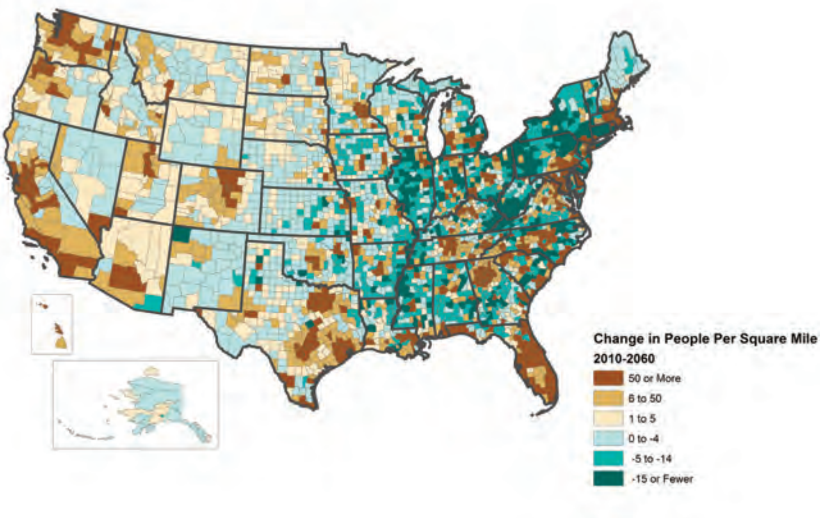
Superimposing a map of the current Interstate System on the projected populations and population densities of counties in 2060 (see Figure 4-2) indicates that more heavily and densely populated counties will, with a few exceptions, be connected by the system as it exists today. At present, a total of 1,444 out of 3,142 counties are served by the Interstate System. When counties that fall within 20 miles of the system are included, 2,477 can be considered to have access and 665 to lack access. The projected average population of counties with access to the system in 2060 is 161,800, compared with an average population of 21,400 for counties lacking access. The populations of counties located within 20 miles of the Interstate System are projected to grow by an average of 42,750 by that year, compared with only 1,060 in counties located more than 20 miles from the system.

These county-level projections for 2060 assume that population growth will be particularly strong along I-5 from Washington to San Diego; along I-10 from Los Angeles to Phoenix; along I-40 from Los Angeles to Albuquerque; along I-15 from Los Angeles to Utah; along I-20, I-35, and I-45 spreading from Dallas; along I-20 from San Antonio to Pensacola; along I-75 and I-95 in southern and central Florida; along Interstates in the triangle of Atlanta, North Carolina, and Nashville; along I-95 from Washington, DC, to Boston; and along I-90 and I-94 from Minneapolis to Detroit (Chi [see Appendix E]).

While this analysis indicates that population will continue to grow the most in areas already served by or connected to the Interstate System, the projections also point to some growing counties that do not currently have

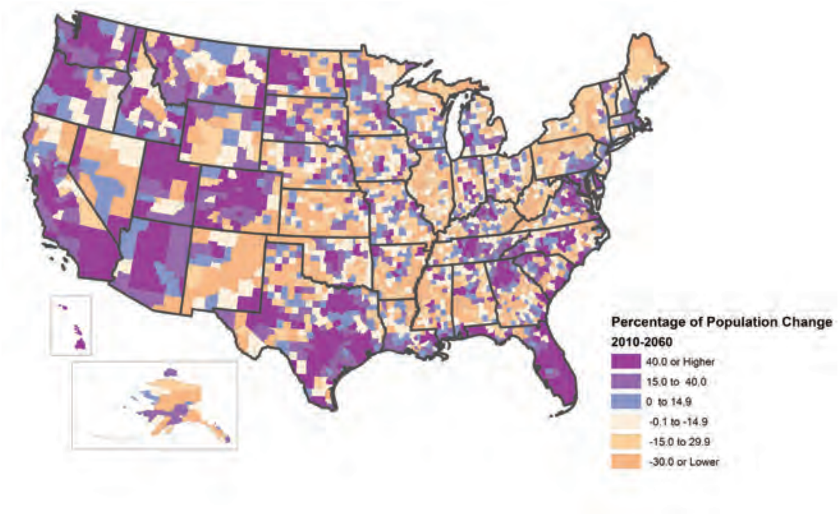


(a) Population Change



(b) Population Density Change

FIGURE 4-1 Population change (a), population density change (b), and percentage population change (c), 2010–2060.
SOURCE: Chi (see Appendix E).



(c) Percentage Population Change

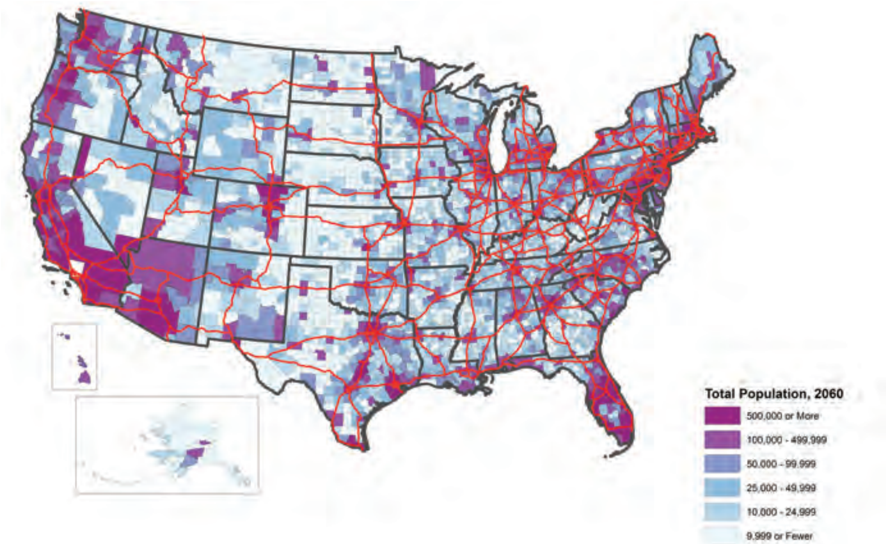
FIGURE 4-1 Continued

access to an Interstate highway (although some of these counties may be located within 20 miles of one). Figure 4-3 shows the counties projected to rank among the top 50 percent of counties in population growth rate and population density from 2010 to 2060 that do not currently have an Interstate highway within their borders. These counties are scattered from the northwest corner of Washington State to the west of Colorado; from the southeast corner of New Mexico to Houston; the tristate area of Montana, South Dakota, and North Dakota; northwest North Dakota; and Hawaii.

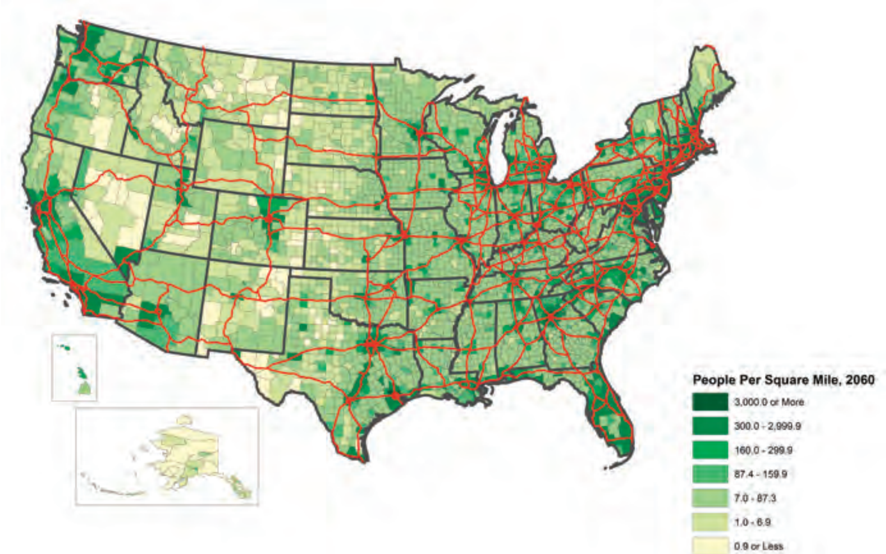
Scope of the Interstate System and the Changing Geography of Economic Activity

The United States is forecast to continue to enjoy overall economic growth over the next several decades, perhaps along the lines of historical increases.[1] While economic growth drives overall traffic growth, it also tends to be accompanied by changes in the location of economic activity (McMullen and Eckstein 2012). Growing economic activity and changes in its location can have far-reaching effects on the amount and mix of automobile and

[1] The U.S. national economy is expected to grow moderately through 2046, with real gross domestic product (GDP) projected to increase at an average annual rate of 2.0 percent. Over the same period, real disposable income per capita is projected to grow at a slightly slower annual rate of 1.6 percent (FHWA 2018a).



(a) Projected Population



(b) Population Density

FIGURE 4-2 Projected population and population density in 2060 compared with the current Interstate Highway System.
SOURCE: Chi (see Appendix E).

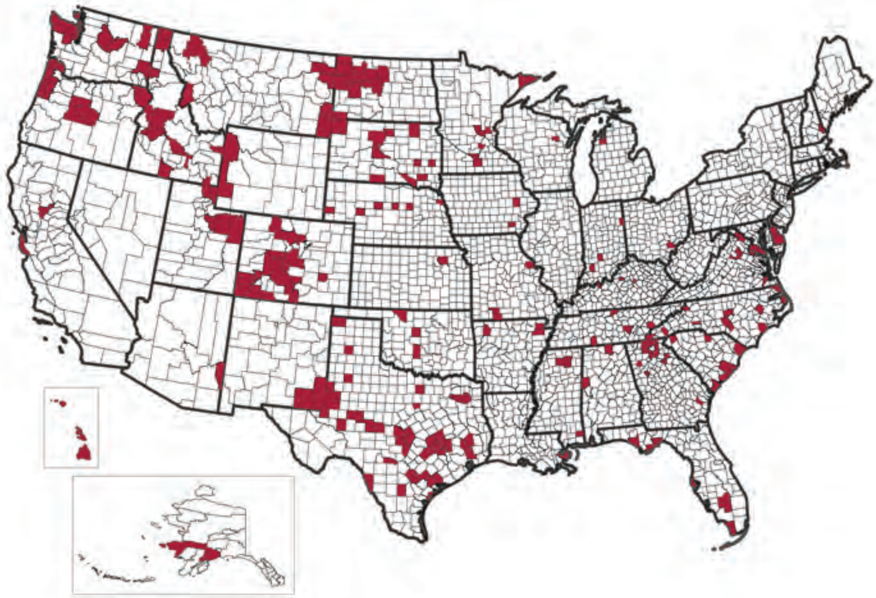


FIGURE 4-3 Counties projected to be among the top 50 percent of counties in population growth rate and density that lack an Interstate highway.
SOURCE: Chi (see Appendix E).

truck traffic, on average trip distances, and on the origin–destination patterns of that traffic.

The core drivers of the U.S. economy are basic industries—such as mining, agriculture, forestry, manufacturing, and technology and supply chain services—that locate where it is most feasible and profitable to do so because they produce goods or services sold widely, across the nation or internationally (Seiber and Weisbrod [see Appendix D]). Their composition, as well as their location, will of course change over time, which in turn will affect the spatial distribution of employment and income. Population growth follows changes in job opportunities in these basic industries, which affect growth in other, more localized industries, such as education, health care, retail sales, and personal services. If the shift to an information economy continues, the growing urbanization of recent decades will also persist.

Figure 4-4 shows schematically how these basic relationships translate further into changes in automotive travel and trucking activity. More employment leads to more commuter trips (AASHTO 2013; see also Sieber and Weisbrod [see Appendix D]). Higher income due to employment growth leads to greater consumption of goods and attendant demand for freight transportation, as well as to increases in the purchase of automobiles and their use for social and recreational trips. Increasing regional economic

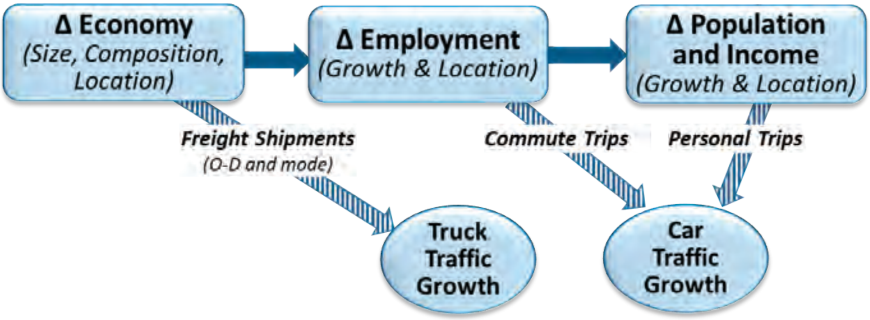


FIGURE 4-4 How changes in the economy affect car and truck vehicle-miles traveled.
NOTE: O–D = origin–destination.
SOURCE: Sieber and Weisbrod (see Appendix D).

specialization in the basic industries can result in even more shifting of the origin–destination pattern of goods and services, with implications for the split of freight mode share and for the location and length of freight trips. More regional specialization also tends to lead to longer shipping distances and to resultant increases in truck traffic on the trunk corridors of the Interstate Highway System.

Figure 4-5 shows how the spatial pattern of job growth in the United States shifted from 1985 to 2015, leading to employment and income losses in some parts of the country and increases in others. While the strength of the relationship among employment, income, and VMT is considered in more detail later in this chapter, that positive relationship supports the conclusion that as changes in the geography of the population occur, the demand for highway access may not align with the existing Interstate System.

Changes in the amount and location of economic activity are not the only drivers of change in demand for highway access; the changing composition of the activity is a factor as well. There are key differences in highway use among industries, particularly in the extent to which they generate truck VMT (see Table 4-2). These differences in highway use among industries can combine with shifting spatial patterns of economic activity to have important implications for the use of highways for freight movement. A measure termed "freight intensity"—defined as the tonnage of freight per job by industry relative to the national average for all industries—indicates how regional changes in employment within an industry can translate into differences in freight demand (Sieber and Weisbrod [see Appendix D]). Figure 4-6 shows changes in freight intensity relative to the U.S. average between 1985 and 2015, affecting changes in industry mix. It is evident that changes in both the location and composition of economic activity have important—and difficult-to-predict—implications.

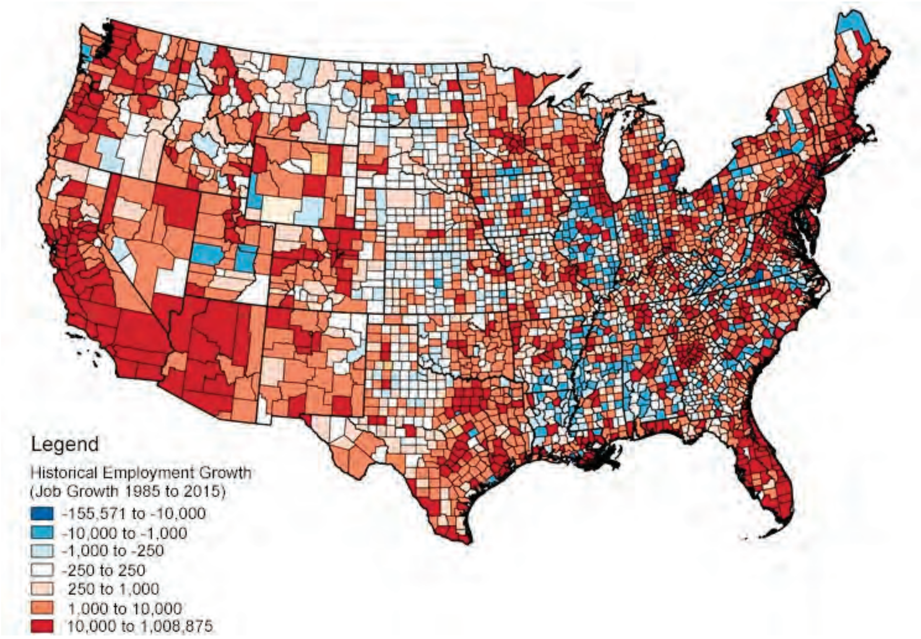


FIGURE 4-5 Change in employment by county, 1985–2015.
SOURCE: Sieber and Weisbrod (see Appendix D).

The Census Bureau provides forecasts of future population by region that can be used to estimate demand for access to Interstate highways. However, forecasting changes in the size and composition of economic activity that will accompany and help drive these population shifts and resultant transportation demand requires consideration of more variables. A set of alternative future scenarios can provide insight into the effects of a changing economy on demand for travel on highways, including Interstates. The scenarios examined for this study employ widely used demographic and economic forecasts of changes in population, number of households, household size and location, workforce size, number of retirees and children, employment, and worker income generated for more than 50 industry sectors. The scenarios differ in assumptions as to which variables will influence economic growth and composition, such as the rate of growth in global markets, productivity, and energy and other resource prices, along with inflation and interest rates.

The base-case scenario leads to an expectation of 42.5 million more jobs in 2045, but with higher-than-average job growth in only 13 industries. Figure 4-7 shows the expected impact of these patterns of industry job growth on population growth, including growth in jobs in service industries that follow shifts in basic industries. Counties forecast

TABLE 4-2 Differences Among Industries in Tonnage, Truck Reliance, Shipment Distance, and Value

Industry	Tonnage (Millions)	Tons per Employee	% by Truck	% by Mult. Modes*	Miles per Shipment	Value per Ton ($1,000s)
Crop Production	1,493	992.5	80.6%	2.4%	637.3	357
Animal Production	237	202.7	91.7%	1.6%	715.6	1,060
Forestry and Logging	337	2,321.1	91.3%	0.1%	1,521.2	49
Fishing, etc.	6	58.0	93.2%	1.9%	366.1	1,349
Oil and Gas Extraction	778	956.9	29.2%	0.5%	77.5	721
Mining, Quarrying, and Support	4,133	5,379.6	61.7%	2.6%	353.7	74
Food Manufacturing	985	545.1	88.5%	2.6%	545.9	1,125
Beverage and Tobacco Product Manufacturing	185	747.1	90.5%	3.1%	315.0	1,658
Textile Mills and Products Manufacturing	33	134.4	88.8%	6.7%	268.2	8,569
Apparel Manufacturing	10	58.0	89.0%	9.2%	340.6	12,996
Leather Product Manufacturing	4	105.4	87.3%	11.6%	613.1	12,594
Wood Product Manufacturing	430	962.5	89.5%	3.1%	787.4	574
Paper Manufacturing	246	653.2	82.5%	3.4%	808.2	982
Printing	18	32.0	92.0%	6.7%	406.5	4,190
Petroleum and Coal Products Manufacturing	3,845	33,362.4	34.1%	0.6%	179.4	596
Chemical Manufacturing	761	963.7	61.8%	2.9%	331.6	2,390
Plastics and Rubber Products Manufacturing	107	151.8	78.4%	4.3%	649.2	3,252
Nonmetal Mineral Product Manufacturing	1,029	2,403.3	92.0%	1.7%	488.7	205
Primary Metal Manufacturing	375	924.0	79.8%	3.9%	731.9	1,218
Fabricated Metal Manufacturing	235	155.3	89.4%	3.1%	543.4	2,409
Machinery Manufacturing	123	107.8	91.9%	3.3%	2,181.7	5,958

TABLE 4-2 Continued

Industry	Tonnage (Millions)	Tons per Employee	% by Truck	% by Mult. Modes*	Miles per Shipment	Value per Ton ($1,000s)
Computer and Electronic Manufacturing	53	54.3	87.8%	8.9%	333.1	19,062
Electrical Equipment and Appliance Manufacturing	40	99.1	92.1%	4.6%	785.6	10,803
Transportation Equipment Manufacturing	270	167.6	85.0%	5.1%	381.2	5,461
Furniture Manufacturing	55	130.5	95.8%	1.6%	408.6	4,903
Miscellaneous Manufacturing	72	106.2	88.5%	6.8%	274.5	7,835
Wholesale Trade	384	59.6	96.3%	1.5%	431.8	3,644
Media and Information	19	5.5	92.3%	6.2%	361.0	4,111
Business Services	248	20.7	92.6%	1.7%	517.3	123

NOTE: * = Multiple modes include truck–rail, truck–air, and truck–marine shipments.
SOURCE: Sieber and Weisbrod (see Appendix D).

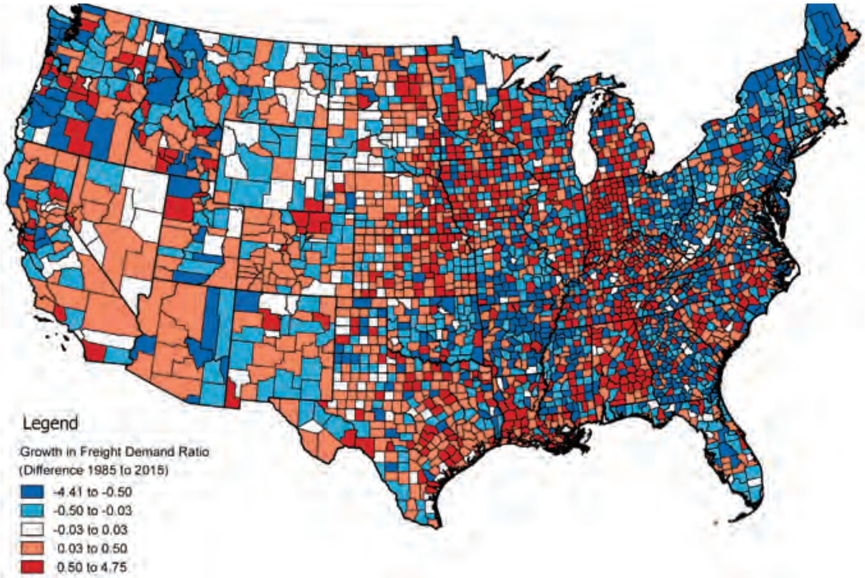


FIGURE 4-6 Changes in freight intensity relative to the U.S. average by county, 1985–2015.
SOURCE: Sieber and Weisbrod (see Appendix D).

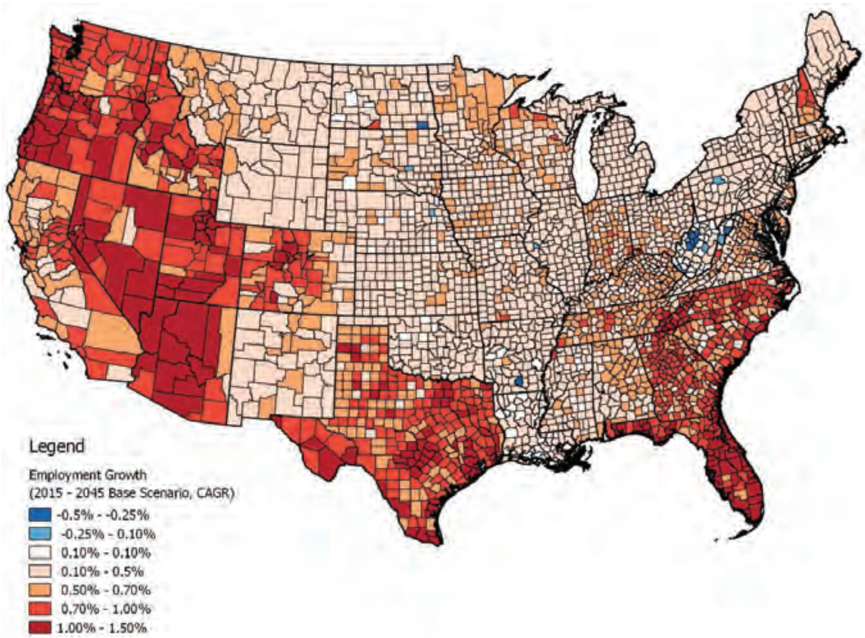


FIGURE 4-7 Forecast change in employment by county, 2015–2045.
NOTE: CAGR = compound annual growth rate.
SOURCE: Sieber and Weisbrod (see Appendix D).

to have higher-than-average growth include some areas that are already fast-growing, including southern California, the San Francisco Bay Area, the Texas triangle, southern Florida, and certain other metropolitan areas. Such a pattern would be expected to add further to demand for highways in the country's metropolitan areas and megaregions.

Figure 4-8 shows how this geographic pattern of industry growth could lead to changes in freight intensity (relative to the U.S. average change), thus shifting demand for truck transportation. The forecast pattern of industrial activity indicates growing freight intensity in parts of the West, South, and Southeast/Mid-Atlantic regions.

Because of uncertainty about future economic changes, the committee considered alternative scenarios that, for instance, assume stronger U.S. economic prosperity, protracted economic slumps, and lower fuel and transportation costs (see Figure 4-9). The expected impacts of lower fuel and transportation costs on freight volumes vary significantly across industries to affect portions of the highway network differently. For instance,

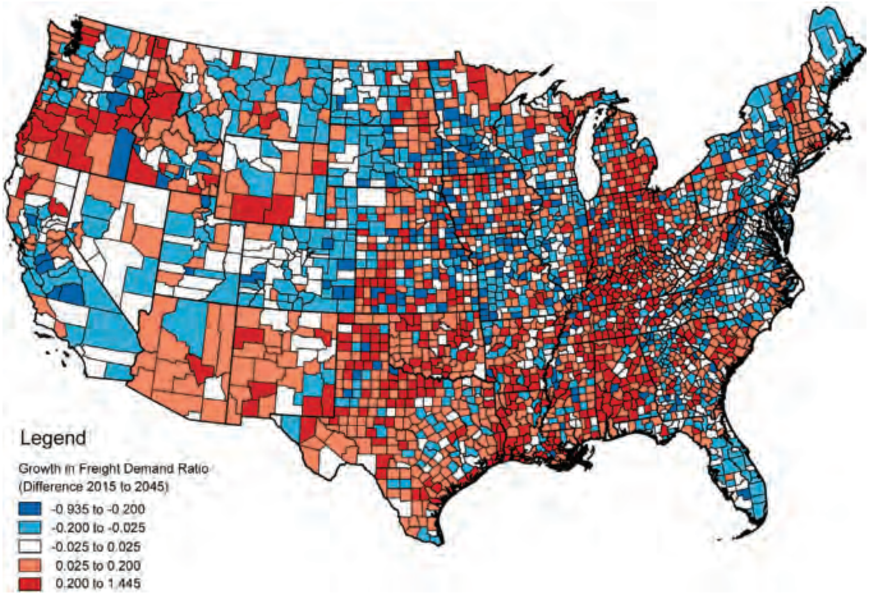


FIGURE 4-8 Forecast change in freight intensity relative to the U.S. average by county, 2015–2045.
SOURCE: Sieber and Weisbrod (see Appendix D).

reductions in freight tonnage (blue lines in Figure 4-9) would be expected on highway routes in areas that experience reduced demand for energy, such as states that produce petroleum and shale oil that are adversely affected by lower fuel prices. Conversely, increases in freight tonnage (red lines in the figure) would occur under this scenario on highway routes where manufacturers and shippers benefit from the lower energy prices to gain productivity and profitability.

While similar calculations and visualizations can be prepared for other scenarios, the purpose of this exercise was to illustrate how a changing economy, coupled with changing demographics, can have important implications for demand on the Interstate Highway System. Keeping pace with the country's economic and demographic changes is important to ensure that the Interstate System is configured to meet new spatial and capacity demands for passenger and freight traffic. In the next section, the committee considers economic, demographic, and other developments that may translate into changes in travel demand, specifically on the Interstate System, over the next several decades.

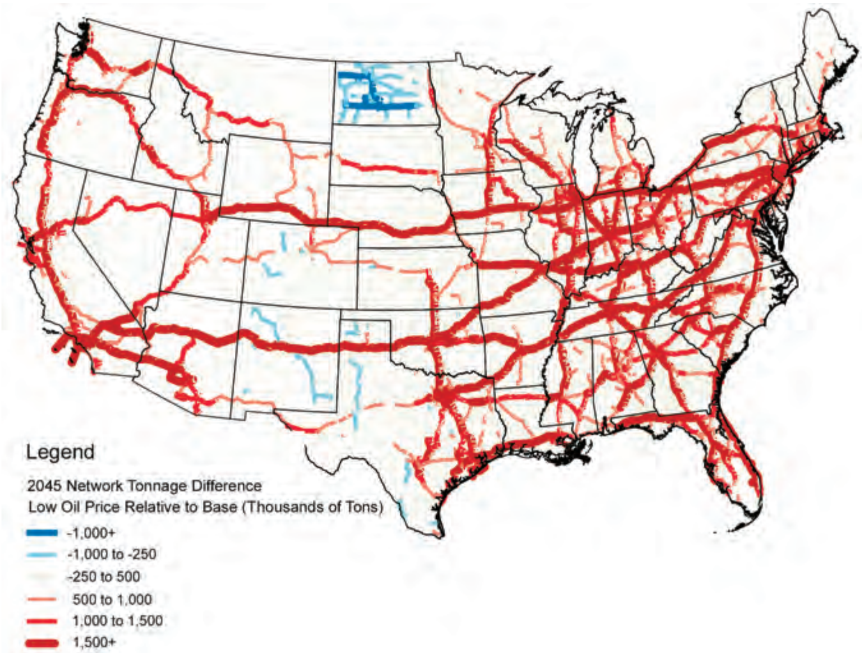


FIGURE 4-9 Changes in freight flows for a future scenario with lower fuel and transportation costs.
SOURCE: Seiber and Weisbrod (see Appendix D).

FUTURE TRAVEL DEMAND AND THE INTERSTATE SYSTEM

At a Glance

- Some of the factors that drove vehicle-miles traveled (VMT) during the last half of the 20th century are no longer impactful, while new ones have emerged that could have significant relevance to future travel trends.
- The moderation of travel demand growth that began in the early 2000s is presumed, but not entirely proven, to be associated with a cyclical decline in the economy (Great Recession), thereby complicating the forecasting of future trends in travel.
- Continuation of past trends in VMT demand on urban Interstates would result in large increases in travel on urban systems that would further tax their already stressed capacity. The policy choices associated with such capacity expansion will entail complex social, environmental, and financial considerations.

The factors that have historically influenced trends in motor vehicle travel, at least over the past half century, have been well studied and provide insight into how travel trends will change in the future and affect the use of Interstate highways. Past trends in VMT have been influenced by numerous factors, many of which (e.g., rising income, population growth) should continue to influence future travel demand. Conversely, some factors that drove VMT during the last half of the 20th century (e.g., women entering the workforce in larger numbers) are no longer impactful, while new ones (e.g., e-commerce, retiring baby boomers) have emerged that could have significant relevance to future travel trends.

Figure 4-10 shows the long-term trends in VMT and U.S. population growth since 1900. Annually, from 1945 through 2005, VMT increased at an average rate of more than 4 percent, while population grew by slightly more than 1 percent. During that same period, the annualized rate of growth in gross domestic product (GDP) was slightly more than 3 percent. For much of this 60-year period, major changes were taking place in both the American economy and society that contributed to the higher rate of growth in VMT relative to population. These changes included women joining the workforce and becoming licensed to drive in large numbers; the

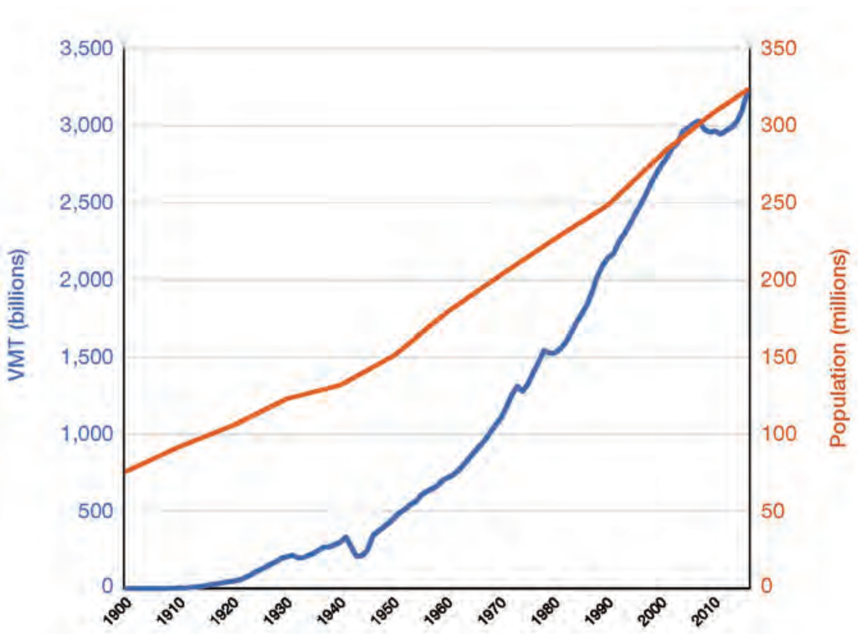


FIGURE 4-10 Annual U.S. trends in growth in vehicle-miles traveled (VMT) and population, 1900–2016.
SOURCE: Polzin (see Appendix C).

baby boom cohort reaching adulthood and forming households; and the post–World War II acceleration of the decentralization and suburbanization of metropolitan areas, spurred in part by the building of freeways. By the 1990s and early 2000s, many of these developments had started to play out as the ratio of male to female drivers reached parity, as baby boomers were reaching late middle age, and as the freeway building boom came to an end.

Although the aging of the baby boom cohort and other demographic and socioeconomic changes were predictable, few travel forecasters anticipated the moderation in travel demand growth that would ensue in the early 2000s. Figure 4-11 shows trends in national VMT and VMT per capita since 1992. For more than a dozen years, VMT per capita has remained below its peak in 2003–2004, but total VMT has rebounded since the Great Recession.[2] The causes of this plateauing in VMT per capita remain unclear, although the decline in VMT in the late 2000s could be attributable to the Great Recession.

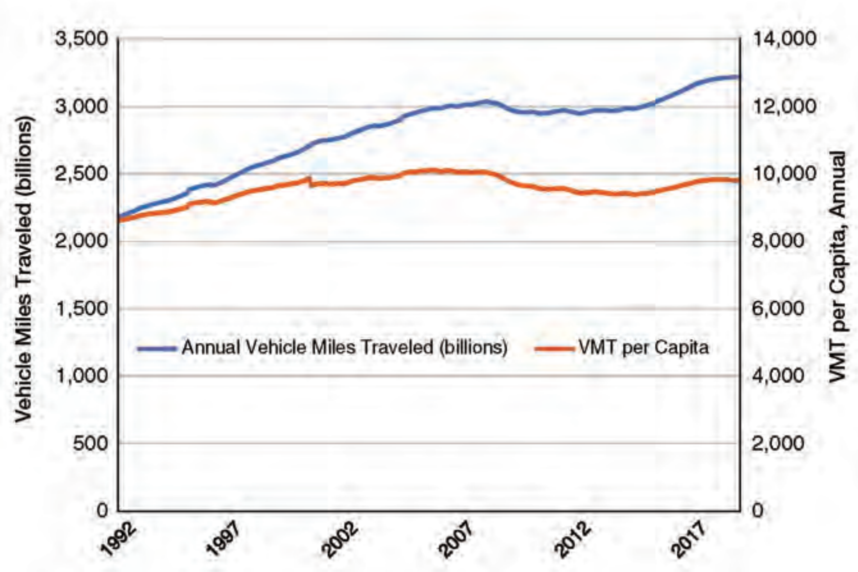


FIGURE 4-11 Trends in national vehicle-miles traveled (VMT) and VMT per capita, moving 12-month totals, 1990–2017.
SOURCE: Polzin (see Appendix C).

[2] Between 2005 and 2015, population grew at about 0.9 percent per year; annualized GDP growth was about 1.72 percent (with negative GDP growth in 2008 and 2009); and VMT rose by a total of 105 billion miles, with growth declining to a maximum of -1.8 percent annually in 2008 and starting to increase again by 2012 (Google n.d.-a, n.d.-b). By 2015, annual growth in VMT was already above 2 percent (FHWA 2015).

Because travel demand is influenced by many factors, analysts have studied various components of demand to identify those factors that may explain this recent changing pattern of travel. These efforts have been largely unsuccessful, and there remains a great deal of uncertainty in demand analyses as to the causes of this development. This uncertainty, in turn, hinders the forecasting of future trends in travel. Thus, even if U.S. population is projected to grow by more than one-third over the next 40 years, how this growth will translate to changes in VMT, and to demand on the Interstate System, remains in question.

By way of example, demographers can predict with reasonable confidence that the U.S. population as a whole will age over the next 50 years. It is well understood that older people have historically driven less than younger people; they make fewer daily trips, travel shorter distances, and have shorter travel times relative to those under age 65. They also do the bulk of their driving at different times of the day than younger people because they are more likely to be out of the workforce, and thus less likely to contribute to the traffic of peak commuting periods. According to projections, the share of people aged 65 and older will increase from 13 percent of the population to more than 23 percent between 2010 and 2060 (see Figure 4-12) (Chi [see Appendix E]). The number of people aged 65 and older will double, from just more than 40 million to more than 98 million. Notably, the oldest segment of the population, those aged 80 and older, will increase from 11 million in 2010 to 40 million by 2060. However, considerable uncertainty remains as to how this aging population and its travel behavior will continue to affect VMT trends. Studies have shown that increasing

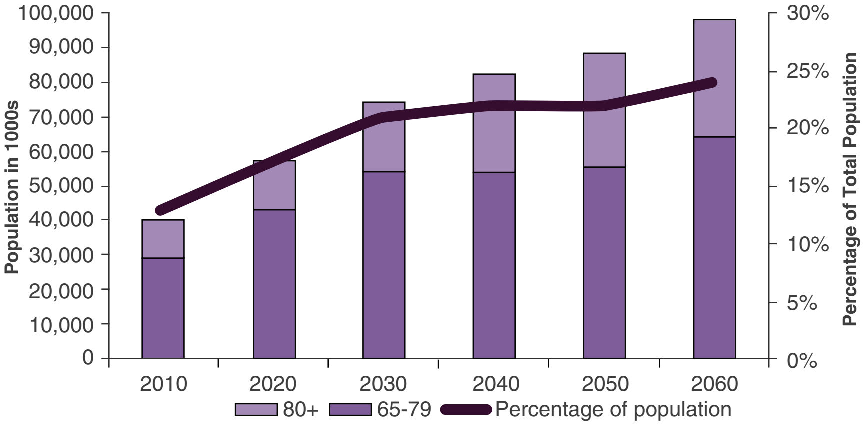


FIGURE 4-12 Projected aging population (aged 65 and older) in the United States, 2010–2060.
SOURCE: Chi (see Appendix E).

numbers of older people hold driver's licenses and drive. They have grown accustomed to using automobiles for most daily activities, and many live in the suburbs without alternative transportation means available. Even if the elderly do not drive as much themselves, they may still require the conveniences of the highway system through their use of online and delivery services and shared-vehicle services. Technology also could have a major impact, with fully automated vehicles providing the opportunity for the use of private cars by those lacking driving licenses.

Future VMT will be affected not only by demographics but also by changes in GDP; household income; and other economic conditions, such as fuel prices, trade, and economic productivity. While trends in some of these variables can be projected with a reasonable degree of confidence, they collectively add to the uncertainty inherent in forecasting highway travel over many decades. The dynamics of differences in freight intensity across industries and the effects of changes in the mix of industries on demand for access to the Interstate Highway System discussed earlier also can affect the amount of truck and commercial travel on the highway system. Changes in the U.S. role in the global economy with respect to major industries such as mining, manufacturing, and agriculture, for example, could have significant implications for trucking (Polzin [see Appendix C]). Other economic and business developments that could affect highway demand include new technologies that will change the relative competitiveness of rail and truck modes. The same observation applies to business practices, such as widespread adoption of same-day deliveries, that affect logistics strategies.

The role of technology and its effects on passenger travel are evolving and remain largely unclear. Email, social media, and smartphones have allowed many people to incorporate some elements of telecommuting into their jobs. Technology-aided developments are expanding local transportation options, such as by making public transit easier to navigate because of the availability of real-time information of schedule status and routing options. Yet, while some forecasters have assumed that telecommunications and information technology will decrease the need for highway travel, research is showing that their impacts have been mixed (Mokhtarian 2009). Ridership in shared-vehicle services, for instance, has implications for local travel on urban segments of the Interstate System. If these services facilitate pooled trips, they may reduce overall trips on urban Interstates, especially during peak periods. Alternatively, if they draw traffic away from transit and increase the total number of vehicle trips, they may compound peak-period congestion on the urban system.

Historically, growth in Interstate demand has not been uniform, but concentrated on the urban system. Figure 4-13 shows the relative role of

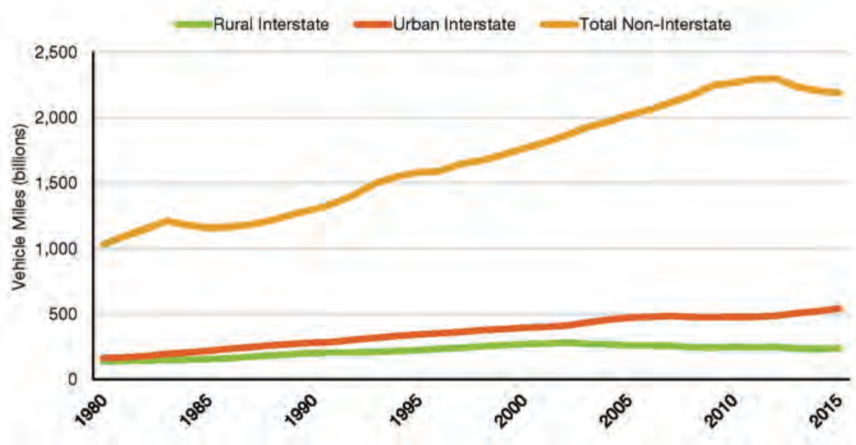


FIGURE 4-13 Role of urban and rural Interstates in accommodating vehicle-miles traveled.
SOURCE: Polzin (see Appendix C).

urban and rural Interstates in accommodating national VMT. The trends reveal that urban Interstates have been playing an increasingly important role in accommodating VMT, while the role of rural Interstates has diminished. Should these trends continue, as appears likely, even modest rates of growth in VMT, measured nationally, may be indicative of disproportionately large gains in travel on urban Interstates that will further tax their capacity.

The substantial uncertainty about future travel behavior and underlying economic, social, and technological conditions—including the prospect of transformational impacts from the introduction of more automated vehicles (discussed later)—favors a strategy of accommodating various scenarios of future demand. At the national level for the next 20 years, an assumption of annual VMT growth that is roughly equivalent to the Census Bureau's base forecast rate of population growth (approximately 0.75 percent per year) is reasonable as a low-end estimate (Polzin [see Appendix C]). On the high end, a VMT growth rate about three times greater (on the order of 2 percent per year) would account for an assumption of strong economic growth driving additional travel demand. Sustained VMT growth rates far beyond this range (higher or lower) would be expected only in the face of pronounced changes in the economy (e.g., prolonged contraction or growth periods) or dramatically impactful technology. With regard to the latter, maturation and market penetration of self-driving vehicle technologies might suggest very different rates of long-term growth in

VMT. At this point, however, those effects remain altogether unclear, not only in magnitude but also in direction.

FUTURE IMPACT OF CONNECTED AND AUTOMATED VEHICLES ON THE INTERSTATE HIGHWAY SYSTEM

At a Glance

- The development and deployment of connected and automated vehicle technology could have multiple impacts on the future Interstate Highway System, some likely to reduce vehicle-miles traveled (VMT) and some likely to increase it. The magnitude and net direction of these VMT impacts is extremely difficult to estimate, as is their timing. In the case of fully automated vehicles, the societal acceptance of such vehicles is unknown at this time.
- A reasonable expectation is that the nation's highway system will continue to be populated by a mix of vehicles with widely varying levels of automation and human operation for at least the next 20 years.
- A 50-year time frame should be adequate to resolve some of the more daunting technological challenges known today to be associated with connected and automated vehicles. However, so much else in the economy and society could change that translating the deployment of such technologies into forecasts of Interstate demand and supply would be highly speculative.

When it was built, the Interstate System was highly innovative, providing faster and safer travel through a range of innovations that included limited access, graded interchanges, cleared roadsides, and medians that separate traffic directionally. From the perspective of a motorist traveling on Interstate highways and other freeways today, perhaps the most perceptible change in the system over the past 20 years has been the installation of electronic toll collection and the availability of real-time information on traffic conditions. By reducing backups at toll booths and providing travelers with detour options, these technological innovations have countered some of the highway system's congestion problems (TRB 2016). Improvements in work-zone signage, configurations, and protective barriers have made the system safer for highway workers as well as motorists.

With respect to the driving experience on the Interstates, however, perhaps the most impactful innovations have emerged in the motor vehicle itself. Vehicle innovations now taken for granted, such as reliable radial tires, quiet interiors, and air-conditioning, have made driving more reliable and attractive. During the past 20 years alone, electronic systems providing convenience and safety features have proliferated in the automobile. Smartphones, Internet access, and video players help entertain passengers on longer trips and during traffic delays, potentially making highway travel less onerous. Motorists have less fear of being stranded by mechanical failure because modern cars are significantly more reliable than earlier vehicles, and mobile phones can be used to request help in the event of an emergency. GPS navigation has made driving less stressful on unfamiliar routes and during poor weather conditions. The introduction of other communication, sensing, and onboard electronic systems has helped drivers control their vehicles—for example, by taking evasive actions, maintaining safe following distances and lane positioning, and providing blind-side warning (TRB 2016).

Collectively, one could make the case that these technological developments have been transformative. Potentially on the verge of widespread introduction, however, are technologies and technological systems that promise even greater change in how people travel and how freight is moved. Notable among these are connected and automated vehicle (CAV) technologies, whose development and deployment could affect the future of the Interstate Highway System. Connected vehicle systems exchange information among vehicles and between vehicles and the roadway infrastructure, while automated vehicle systems may relieve drivers of some, or perhaps all, of the tasks associated with controlling and navigating the vehicle. These technologies are reviewed briefly in Box 4-1 and in depth in Appendix F.

Critical to the question of how these systems will affect the future of the Interstate Highway System are their prospective impacts on the demand and supply sides of the system. Demand effects, increasing and decreasing, are expected to include the following (Shladover [see Appendix F]):

- Reductions in the need to travel resulting from the opportunity to substitute telecommunications.
- Changes in trip scheduling, with better information promoting better choices for avoiding the worst congestion and safety challenges.
- More efficient selection of routes and modes of travel based on better information about viable alternatives.

BOX 4-1
Connected and Automated Vehicle Technologies

Vehicle-to-vehicle (V2V) connectivity can enable such applications as the following:

- Cooperative collision warnings and hazard alerts
- Cooperative collision mitigation or avoidance, incorporating active braking
- Cooperative adaptive cruise control, with tighter vehicle-following control relative to conventional adaptive cruise control and enhanced traffic flow stability
- Close-formation automated platooning, enabling aerodynamic drafting and lane capacity increases
- Automated maneuver negotiation at merging locations or intersections
- Transit bus connection protection

For most of these applications, the communicated data are used to augment the data acquired by onboard remote sensors, which remain the primary source of data on time-critical and safety-critical conditions.

Infrastructure-to-vehicle (I2V) connectivity can enable the following:

- Providing drivers with traffic signal status information in real time for in-vehicle display, signal violation warning, or green wave speed advisories
- Providing drivers with information on traffic and weather conditions and real-time routing advisories
- Fleet management functions of vehicle routing and scheduling
- Access control to closed facilities
- Variable speed limits and advisories provided directly to drivers or their vehicles (I2V cooperative adaptive cruise control)
- End of queue warnings
- Active support for lane guidance

- Reduction in the disutility of travel time, thereby encouraging realization of latent demand and potentially inducing new travel demand through locational changes.[3]
- Improved quality of transit service, encouraging shifts in passenger mode away from personal vehicles and toward transit.
- Electronic chauffeuring, providing affordable mobility for travelers who cannot drive, thus encouraging them to travel more than before.

[3] "Locational changes" is a land use planning term that refers to people deciding to move to a home in a different location or businesses deciding to move their offices or shops to a different location. In the context of this chapter, if a long commute trip is not so burdensome, individuals may decide to buy a larger house on a larger plot of land farther away from their workplace.

Vehicle-to-infrastructure (V2I) connectivity can enable the following:

- Vehicle probe data applications providing detailed traffic information (speed, volume, travel time, queue length, stops) or information on road surface conditions (pavement roughness or slippery conditions)
- Mayday and concierge services (such as OnStar)
- Electronic toll collection and parking payments
- Traffic signal priority requests
- Vehicle status information for fleet management (especially for transit and trucking fleets)

Automated vehicles are categorized as follows, depending on the level of human engagement in the driving task:

- Level 1—The driver must drive other function and monitor the driving environment. Technologies include adaptive cruise control or lane-keeping assistance.
- Level 2—The driver must monitor the driving environment (the system nags the driver or deactivates itself so as to ensure this). Technologies include adaptive cruise control and lane-keeping assistance, traffic jam assist for freeways, and parking with external supervision.
- Level 3—The driver may read a book, text, or Web surf, but must be prepared to intervene when needed. In addition to the technologies in Level 2, the vehicle includes traffic jam pilot technology.
- Level 4—The driver may sleep, and the system can revert to minimum risk condition if needed. Examples of this level of automation include highway driving pilot, closed-campus "driverless" shuttle technology, and "driverless" valet parking in garages.
- Level 5—The vehicle can operate anywhere, with no driver needed. This level of automation includes ubiquitous automated taxi (even for children) and ubiquitous car-share repositioning systems.

- Increased efficiency and improved quality of service by trucking—potentially including higher-quality, real-time traffic and weather information that enables truck operators to choose better routes, and platooning of trucks that increases the capacity and smooths the traffic on congested truck corridors—encouraging a freight modal shift toward trucking.

CAV technologies could have even greater supply-side effects by producing changes in multiple aspects of traffic operations that would have effects on safety, travel times, congestion, energy use, emissions, and travel comfort and convenience such as the following:

- Changes in traffic flow stability[4] based on differences in vehicle-following dynamics.
- Changes in highway lane capacity based on differences in vehicle-following gaps.
- Increases in highway bottleneck throughput based on more responsive traffic management and the ability to implement situation-dependent speed control.
- Reduction in traffic disturbances from lane drops[5] and entrance and exit ramp flows through coordinated vehicle merging.
- Improved ability to manage incidents based on higher-fidelity information for incident responders, as well as for travelers.
- Improved multimodal corridor management in urban areas through enhanced information and control mechanisms.

It is apparent that some consequences of CAV deployment will reduce VMT, while others will increase it. If the mobility enhancement effects dominate on the demand side, VMT is likely to increase unless ride sharing in automated jitney services becomes the preferred mode of urban and suburban transport, in which case VMT could decrease. The supply-side effects would presumably affect VMT by making highway travel safer and more efficient, but assessing the magnitude of those effects at this stage would be extremely tenuous.

Not only is the magnitude of the consequences of CAV deployment difficult to estimate, but its timing is also highly uncertain because of unknowns regarding the pace of technology advances, the rate of user acceptance of the technology once it has been developed, and the length of time required to change the vehicle fleet and highway infrastructure. Forecasting the development of information technology is fraught with uncertainty, as this realm is characterized by short-interval cycles of technological change. The life of a generation of integrated circuits is about 18 months, for example, whereas automotive vehicles are designed and manufactured for service lives of more than a decade, and highway infrastructure requires planning horizons of up to 50 years, and real-world implementation times are likely to be governed by the slowest of the relevant influences (Shladover [see Appendix F]). A serious technological issue that could slow the introduction of CAV technology is the need to ensure sufficient protection against cyber attacks. Providing cybersecurity, already a challenge for contemporary vehicle electronics systems, could become far more demanding as attackers

[4] In this context, stability refers to desired patterns of density and velocity profiles.

[5] Lane drops are defined as locations on a roadway where there is a decrease in the number of lanes for through traffic.

are tempted to target highly automated vehicles or collections of connected vehicles.

A reasonable expectation is that the highway transportation system will continue to be populated by a mix of vehicles with widely varying levels of automation for the foreseeable future, at least for a period of 20 years or more. Manually driven vehicles will continue to be part of the mix, along with vehicles using lower levels of automation to enhance safety and the traveling experience, even after more highly automated vehicles become selectively available for public use. Within 20 years, vehicle connectivity of one type or another is likely to become virtually ubiquitous, providing comprehensive information to travelers and transportation system operators to assist them in making better decisions (Shladover [see Appendix F]). In preparation for this development, the Federal Highway Administration has begun exploring the ways in which the highway infrastructure will need to be adjusted to accommodate these technologies (FHWA 2018b).

Recent and ongoing experience with the introduction of advanced vehicle technologies supports a cautious assessment of CAV deployment rates. Figure 4-14 shows how a front-crash prevention feature, automatic emergency braking, has been introduced and taken up in the vehicle fleet. By 2016, 45 percent of new vehicle models offered automated emergency braking as a standard or optional feature, increasing every year from their introduction a decade earlier. However, despite the increasing availability of this feature, only about 5 percent of vehicles on the road were equipped in 2016. The insurance industry estimates that automatic emergency braking systems will not be incorporated in a majority of registered vehicles until somewhere between 2025 and 2030 (see Figure 4-15).

An inability to forecast future demand-and-supply side impacts of CAV deployment is problematic for the planning of the future Interstate System, with its many long-lived assets. It will thus be important for transportation decision makers contemplating infrastructure investments and mobility needs not to commit themselves to becoming overly dependent on any one expected outcome based on the anticipated availability of a particular technological capability by a specific future date (Shladover [see Appendix F]).

A review of the literature by Polzin in Appendix C finds wide-ranging estimates of how the introduction of CAVs will affect future rates of growth in VMT. It supports a conclusion that forecasts of VMT beyond 20 years have limited value for most current decision making purposes. While this conclusion does not imply that large travel impacts from CAVs are unlikely over time, only that the status of technology development and introduction will need to be well monitored to ensure that the timing, direction, and magnitude of impacts are recognized early enough to inform decision making. It will also be necessary to adopt strategies that can accommodate

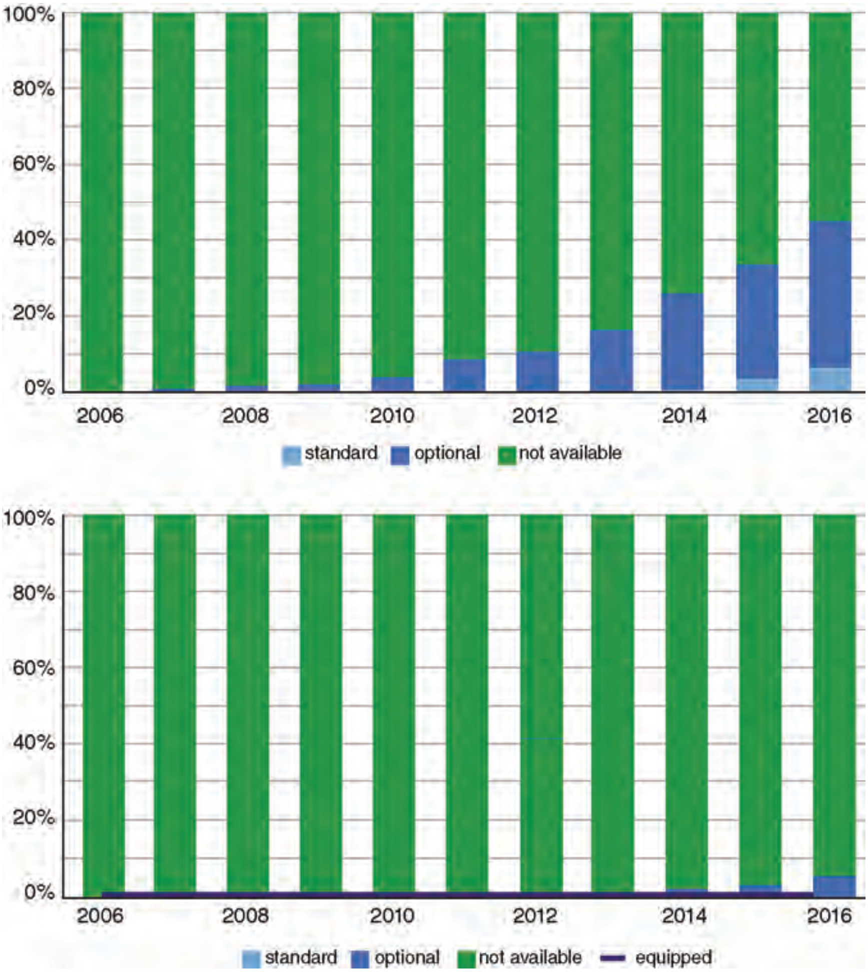


FIGURE 4-14 Share of new vehicle models offering automatic emergency braking (top) and registered vehicles equipped with the feature (bottom).
SOURCE: HLDI 2018.

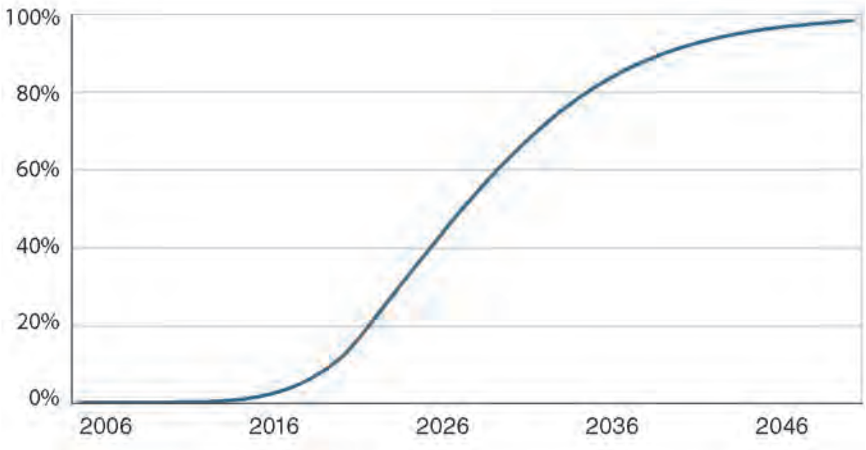


FIGURE 4-15 Estimated future percentage of registered vehicles equipped with automatic emergency braking.
SOURCE: HLDI 2018.

plausible amounts of change and uncertainty, even at the risk of some preparations being less than optimal for actual developments in 20 to 50 years.

CLIMATE CHANGE AND THE INTERSTATE HIGHWAY SYSTEM

At a Glance

- Climate change may accelerate the deterioration of Interstate assets, increase operational disruptions, and cause catastrophic failure of some structures.
- Decisions will have to be made as to how existing and future Interstate System infrastructure can be made less vulnerable and more resilient to the impacts of climate change, and how changes to the system itself can contribute to mitigating some of the causes of climate change and its impacts.

The world has warmed over the past 150 years, a development attributable to the rapid increase in carbon dioxide (CO_2) and other heat-trapping greenhouse gases (GHGs) in the atmosphere since the industrial revolution of the late 1800s (see literature review in Wuebbles and Jacobs [see Appendix G]). While the amount of CO_2 in the Earth's atmosphere has always been cyclical, its concentration has increased sharply over the past six decades (see Figure 4-16). The Earth's climate is changing at a pace and

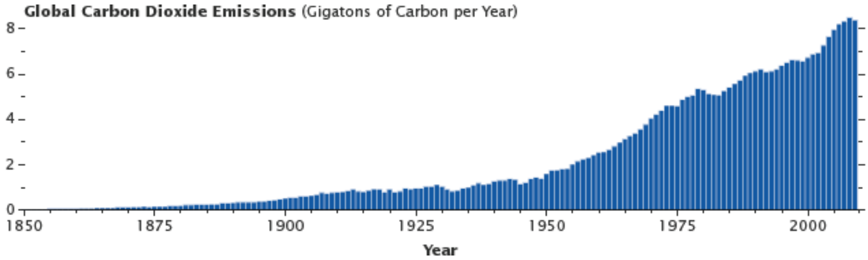


FIGURE 4-16 Global emissions of carbon dioxide (CO_2) from human activity.
SOURCE: NASA n.d.

in a pattern not explainable by natural influences and many different lines of evidence demonstrate that human emissions of GHGs are largely responsible for these changes (Wuebbles and Jacobs [see Appendix G]).

A large and looming consideration for decision makers contemplating the future of the Interstate Highway System is how these changes in the Earth's climate system and associated impacts on temperature, precipitation, sea level, and other climate conditions will affect the nation's transportation infrastructure and how the adverse effects can be mitigated. Given the Interstate System's central role in the overall U.S. transportation system, its future integrity and functioning are especially important considerations.

Of particular concern is the strong evidence of an increasing trend in recent decades of certain types of extreme weather events in terms of frequency, intensity, and duration, as well as resulting impacts on society—a trend cited as among the most important consequences of a warming climate (Wuebbles and Jacobs [see Appendix G]). Among such extreme weather events are high-temperature and heavy-precipitation events that include more intense and more midlatitude hurricanes and tropical storms, cyclones, and hail and tornadoes associated with thunderstorms. Sea level rise also is closely linked to increasing global temperatures. While uncertainty remains as to just how much sea levels will rise during this century, it is virtually certain that they will rise and pose a growing challenge to coastal communities, infrastructure, and ecosystems as a result of such outcomes as increased inundation, more frequent and extreme flooding, and erosion.

Existing research indicates that in the coming decades, both the frequency and intensity of extreme weather events are likely to increase (Wuebbles and Jacobs [see Appendix G]). Especially relevant outcomes with respect to transportation infrastructure will be increases in intense precipitation events, increased Arctic temperatures (leading to permafrost melting), sea level rise, very hot days and heat waves, and increased hurricane intensity. For the Interstate Highway System in particular, climate variability and change may accelerate asset deterioration, cause operational and service disruptions, and contribute to the catastrophic failure of some structures. Notable impacts identified by the U.S. Department of Transportation (U.S. DOT 2014) include the following:

- More frequent/severe flooding of underground tunnels and low-lying infrastructure due to more intense precipitation, sea level rise, and storm surge, requiring enhanced drainage and pumping;
- Increased frequency and magnitude of storm surges and relative sea level rise, potentially shortening infrastructure life;
- Increased thermal expansion of paved surfaces due to higher temperatures and increased frequency and duration of heat waves, potentially causing degradation and reduced service life;
- Higher maintenance/construction costs for roads and bridges due to increased temperatures and exposure to storm surge;
- Asphalt degradation due to higher temperatures and shorter replacement cycles, leading to limited access, congestion, and higher costs;
- Damage to culvert and drainage infrastructure due to changes in precipitation intensity and snow-melt timing;
- Decreased driver/operator performance and decision-making skills due to driver fatigue as a result of adverse weather; and
- Increased risk of vehicle crashes in severe weather.

Changing seasonal precipitation, increased rainfall intensity, and snow and rain transitions also are likely to affect the Interstate Highway System in a number of ways, most dramatically through the elevated risk of flooded highways, tunnels, drainage systems, and connected secondary roads (Wuebbles and Jacobs [see Appendix G]). The Interstate System's vulnerability to flood events and mudslides due to long-duration rainfall is demonstrated by five major flooding and mudslide events during the first half of 2017 that shut down segments of the system—including northern (I-80) and southern California (I-880) in January; north central California (I-5) in February; Idaho (I-86) in March; and the central United States, including Missouri (I-44 and I-55) in May—for days or weeks. While all regions may encounter increased flooding impacts from climate change, the Northeast is particularly at risk due to increasing heavy rainfall, while the Pacific Northwest faces increased slope stability challenges, and the upper Midwest is increasingly vulnerable to spring floods from changing climate (see Figure 4-17).

Highway agencies will need to prepare for the particular vulnerability of bridges to flooding events (Wuebbles and Jacobs [see Appendix G]). The two most common bridge failure modes are scour, in which bridge

FIGURE 4-17 An on-ramp to Interstate 380 in Cedar Falls, Iowa, flooded as waters rose in 2008.
SOURCE: U.S. Air Force 2008.

foundations are compromised because of erosion, and structural failure during single-event floods. The U.S. Environmental Protection Agency (EPA) estimates that approximately 190,000 bridges overall are vulnerable to the effects of climate change, particularly scour (EPA 2015). Although EPA does not provide estimates specifically for the Interstate System, it estimates that approximately 75 percent of bridges in parts of the Northeast are structurally vulnerable to effects of inland flooding and long-term river flow changes (see Figure 4-18).

As noted earlier, sea level rise is a particular concern for highways located in coastal and low-lying areas. By the end of the present century, global sea levels are projected to rise 1 to 4 feet (Wuebbles and Jacobs [see Appendix G]). Because of differences in topography and development patterns, the resulting threat will vary by region and location, with states along the Atlantic and Gulf Coasts expected to experience greater impacts relative to states on the Pacific Coast (see Figure 4-19). Interstate highway infrastructure in the coastal zones is already vulnerable to extreme weather events—a vulnerability that will increase with sea level rise, storm surge from more tropical and nontropical storms, and land subsidence. Hurricanes Matthew (2016), Sandy (2012), Ike (2008), and Katrina (2005) caused billions of dollars in damage to coastal roadways and bridges,

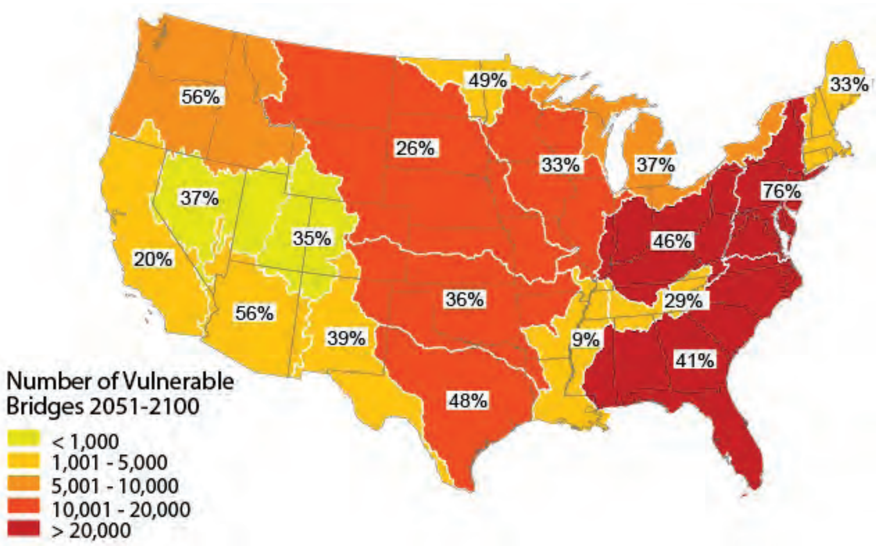


FIGURE 4-18 Bridges identified as vulnerable in the second half of the 21st century as a result of climate change.
SOURCE: Adaptation of Figure 1 in EPA 2015, 34.

including significant economic losses due to transport disruption during and after the storms. Critical Interstate corridors and assets—such as I-95 and I-678 in the New York/New Jersey coastal region—are susceptible to seawater flooding and inundation. I-64, I-264, and I-564 in Virginia's Hampton Roads region are especially vulnerable to rising seas and storm surge. These Virginia highways serve not only a local population of more than 1 million and one of the East Coast's main ports, but also the nation's largest naval base and more than two dozen other military bases and support facilities. Likewise, segments along I-10, I-55, and I-59 on the Gulf Coast are considered vulnerable to rising seas and storm surges.

The choices being made now and in the next few decades about GHG emissions from fossil fuel and land use changes will influence the extent of additional warming over this century and beyond. As with the effects of CAV deployment, however, climate change impacts and needed adaptations must be considered under conditions of uncertainty. Uncertainties about how the economy will evolve, what types of energy will be used, and how cities, buildings, and vehicles will be designed in the future are among the factors that limit the ability to project changes in climate. Given that motor vehicles account for about 25 percent of U.S. GHG emissions and that about a quarter of VMT is on the Interstates, the future use of the Interstate System will be an important part of this choice set.

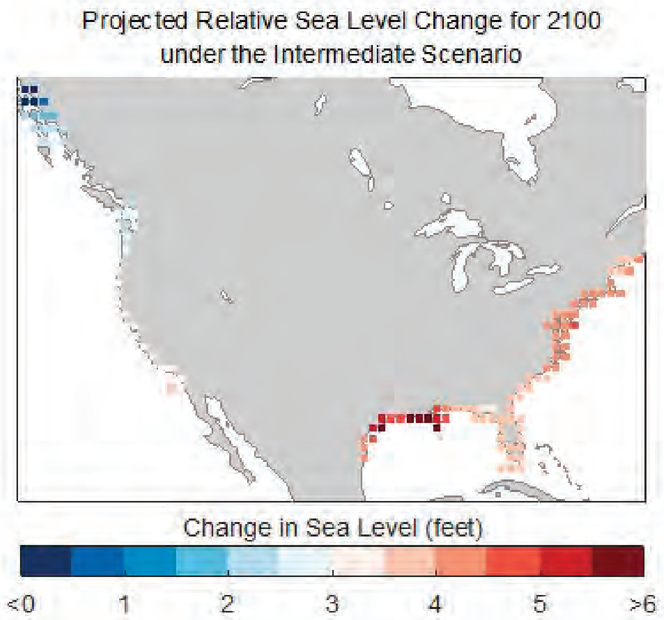


FIGURE 4-19 Regional sea level rise (feet) in 2100 for the United States, projected for the Interagency Intermediate Scenario. Global mean sea level rise is projected to be 1 meter (3.3 feet) by 2100. Much of the eastern and southern United States is projected to experience a larger sea level rise than the global average.
SOURCE: Sweet et al. 2017.

Travel on the Interstates now accounts for about 7 percent of total U.S. annual GHG emissions.[6] How that share will change will depend in part on public-sector initiatives to further the development and use of fuels that produce lower GHG emissions. Some countries, including France, China, and the United Kingdom, as well as some vehicle manufacturers, have announced intentions to phase out vehicles powered by internal combustion; oil companies are investing in charging stations for electric vehicles (EVs) (see Bousso 2017); and some states are embracing electrification through the Zero-Emission Vehicle Memorandum of Understanding (ZEV MOU) (Georgetown Climate Center 2013). California's ZEV regulation, which also has been adopted by nine other states, requires a minimum percentage

[6] Estimate calculated using Interstate VMT values from *Highway Statistics 2016* (FHWA 2016), fleet miles per gallon from the *Transportation Energy Data Book* (edition 36) (Oak Ridge National Laboratory 2018), fuel (gasoline and diesel) CO_2 emissions from EPA (EPA 2005), and adjustment to account for GHGs other than CO_2 from EPA420-F-05-004 (EPA 2005).

of sales of zero-emission vehicles, such as battery electric, fuel cell, and plug-in hybrid. The U.S. Energy Information Administration (EIA) projects that sales of battery electric vehicles will likely grow from less than 1 percent of total vehicle sales in 2017 to 12 percent in 2050 (EIA 2018) (see Figure 4-20). As encouraging as these electric power developments may be, they can best be described as necessary but not sufficient to reduce GHG emissions markedly: today, about two-thirds of America's electricity is generated using hydrocarbon fuels (EIA n.d.).

It merits noting that the Federal Highway Administration (FHWA), through its Alternative Fuels Corridors program (as required by Congress), in collaboration with the states, is facilitating the deployment of alternative fuels by designating highways that meet specified criteria for charging and fueling infrastructure.[7] The stated goal is to ensure that fuel stations offering fast electric charging capability are located no more than 50 miles apart along Interstate routes, are not more than 5 miles from exit ramps, and are accessible to the general public (see Figure 4-21).

Through increased access to recharging infrastructure, and in other ways, the future Interstate System may play a complementary role in

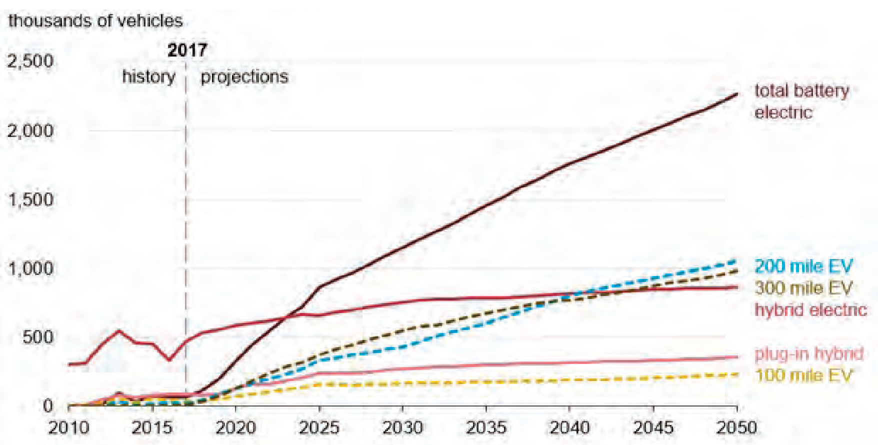


FIGURE 4-20 U.S. sales of battery-powered vehicles.
SOURCE: EIA 2018.

[7] The Alternative Fuels Corridors program focuses on designating Interstate corridors that already have access to alternative fuels (i.e., electricity, compressed natural gas, liquid natural gas, hydrogen, and propane). This annual designation program, started in 2016, entails corridor nominations from the states and evaluation of the corridors against a set of criteria. If a nominated Interstate corridor meets the criteria, it is designated as an Alternative Fuels Corridor. As of March 2018, more than 80 Interstate Alternative Fuels Corridors had been designated in both urban and rural areas; the designated corridors are located in 44 states plus the District of Columbia.

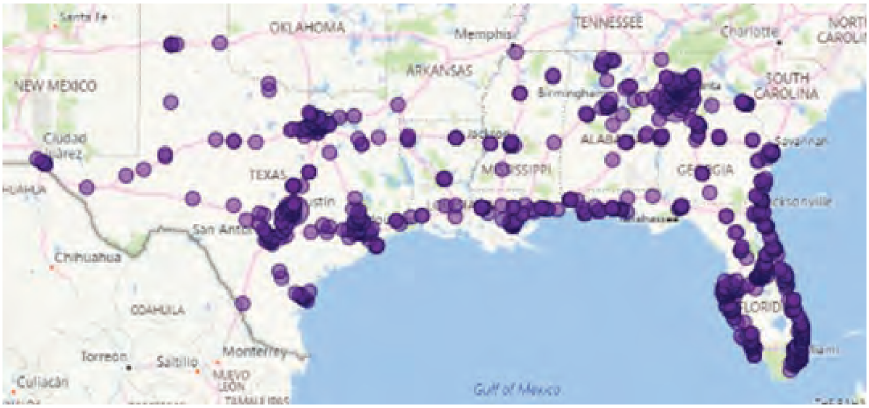


FIGURE 4-21 Electric vehicle charging stations near Interstate highways in the Gulf Coast and lower Atlantic states.
SOURCES: Alternative Fuel Toolkit website, a product of the *Deployment of Alternative Vehicle and Fuel Technologies Initiative,* a joint project of the Oregon Department of Transportation (DOT) and other state DOTs, along with FHWA (http://altfueltoolkit.org/materials/find-an-alternative-fuel-station).

encouraging EV deployment (see Box 4-2). It is even conceivable that in the future, EV recharging will be enabled through the pavement itself, as technologies such as inductive charging (which moves the energy storage from the vehicle battery to the road via charging pads in the road surface or coils embedded in thin strips along the center of a lane) are being piloted in the United States and abroad (Lant 2017). In this regard, the uncertainty faced by decision makers about the future of the Interstate Highway System is multifaceted, involving choices about how the infrastructure should be made more resilient to the ongoing and anticipated adverse impacts of climate change, what provisions should be made in near-term highway construction to allow for the incorporation of future technology opportunities, and how changes to the Interstate System itself can help mitigate the causes of climate change.

SUMMARY

Federal and state decision makers planning and making investments in the Interstate Highway System face numerous uncertainties about the system's future use and development. The system's status over the next several decades is likely to be affected by many factors, from the pace and location of the nation's population and economic growth to potentially transformative changes in technology and in the damaging and disruptive effects of climate change. Uncertainty about the number of influential factors, their

BOX 4-2
Complementarity of the Interstates to Climate Change Mitigation Initiatives

A recent report from the Intergovernmental Panel on Climate Change (IPCC) concludes that global greenhouse gas (GHG) emissions from human activity must be cut nearly in half by 2030 and to a far greater degree by 2050 to slow the rate of global warming (IPCC 2018). The transportation sector is the largest U.S. contributor of carbon dioxide and other GHG emissions, and its share of total emissions is increasing (EPA 2018). As the backbone of the U.S. transportation sector, the Interstate Highway System contributes to these emissions and can thus play an important role in reducing them. Inasmuch as the Interstate Highway System has facilitated low-density suburban development and reliance on automobiles, a transformation to a low- and no-carbon transportation system will increasingly mean that its planning is integrated with the planning of low-carbon mobility options, from public transit to zero-emission trucks.

Many states, counties, and cities are investing in low-carbon transportation solutions, seeking to create new opportunities for both low-carbon mobility and economic development. They are promoting the use of lower-carbon fuels and vehicles, improvements to the operational efficiency of their transportation systems, and alternative transportation modes that do not depend on fossil fuels (U.S. DOT 2010). Currently, 10 states require the sale of zero-emission vehicles (Auto Alliance n.d.), and they and some other jurisdictions are providing incentives for the purchase of electric vehicles (DOE n.d.). Complementary to these policies, states in the Mid-Atlantic and New England are cooperating through the Transportation and Climate Initiative to promote electric vehicle corridors and explore regional low-carbon transportation policy options (Bradbury n.d.). Likewise, states in the Rocky Mountain region are collaborating on planning for the deployment of charging infrastructure that is configured to enable electric vehicles to travel long distances without charging gaps (Goetz n.d.; State of Colorado 2017; West Coast Green Highway n.d.).

interactions, and the potential for each to evolve in various ways creates an environment for decision making that is complex but must be considered when making investments in the Interstate System and other long-lived transportation infrastructure. This chapter has examined the following key factors.

Population and economic growth. Some factors that will almost certainly influence the future demand for Interstate highway transportation, as well as the system's performance and condition—particularly the likelihood of at least moderate population growth—can be anticipated with a reasonable degree of confidence absent catastrophic events. Continued economic growth can also be reasonably expected over a decades-long period, and these two factors together should lead to increased demand for motor vehicle travel in general and on the Interstates in particular. Growth in VMT on the Interstate System averaging between 0.75 percent and 2 percent annually for the next 20 years is a reasonable but admittedly broad planning range, assuming that VMT will largely at least keep pace with projected population growth and possibly increase more rapidly as a result of income and economic expansion. It is reasonable to assume that this added VMT will be concentrated in the country's metropolitan areas, which have seen the greatest growth in population and VMT over the past several decades.

The geographic and sectoral distribution of the country's population gains and economic growth. These factors are also likely to affect the demand for connections to the Interstate Highway System. It is widely expected that most of the country's population gains—and much of the accompanying growth in economic activity—will follow the pattern of the past several decades by concentrating in states of the South and West and their fast-growing cities and metropolitan regions. Sectoral changes in the economy, including the mix of economic activity across industries that are more or less freight-intensive, are also likely to be factors in the future demand for Interstate highway transportation, but these more granular developments are much more difficult to forecast over longer periods relative to overall trends in population and economic growth.

The introduction and widespread deployment of connected and automated vehicles. This potentially revolutionary factor in the future of the Interstate System has implications for both the demand and supply sides of the system. The likelihood of major effects on the system from such deployments over the next two decades appears to be modest because of the need for some still significant technology advances, including safety and cybersecurity assurances; the need to develop and implement protocols and processes for ensuring suitably maintained and equipped infrastructure; and the simple fact that vehicles have become more expensive and durable, lengthening the period of time for turnovers in the vehicle fleet. Beyond a period of 20 or 30 years, and certainly in the decades that follow, the technological changes in this area could be transformative, but in what respect and to what effects—even as to whether VMT increases or decreases—can only be a matter of speculation at this time, particularly when one is considering a single element of the nation's transportation system, that is, the Interstate Highway System.

Climate change. Climate change poses the very real prospect of dramatic effects on coastal and riverine regions due to sea level rise and flooding; increased incidence and severity of extreme and catastrophic weather events; and changes in the norms for weather and environmental conditions that have long been the basis of highway design, construction, and maintenance standards. These developments are likely to have major implications for the future of the Interstate System. Substantial investments will be needed to make the system less vulnerable and more resilient to these effects, starting soon in cases in which long-lived assets are being planned, sited, constructed, and rebuilt. Projections of climate change and its impacts will need to be translated into new and revised highway design and construction standards well in advance of the time at which these impacts become widely manifest, including for routine repair and rehabilitation projects that collectively represent major areas of Interstate investment. Because many needed resiliency investments will be context- and site-specific and implemented over the course of decades as the effects of a changing environment unfold, decision makers today must begin preparing the Interstate Highway System for change that could be dramatic, but must do so with too little information to plan a detailed resiliency program or to grasp the extent of the needed investment. Adaptability may be the coin of the realm.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FHWA	Federal Highway Administration
HLDI	Highway Loss Data Institute
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation

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5

System Investment Needs: A 20-Year Horizon

As the Interstate Highway System enters its seventh decade, the proposition that it can continue to serve the country effectively for many more years without extensive renewal and modernization is unsupportable. Much about the future is unforeseeable, particularly beyond the next two decades, given that, as discussed in the preceding chapter, advances in technology and changes in climate have the potential to affect the system in profound but still indeterminate ways. Yet, despite this uncertainty, the system's future over the next 20 years or so is not imponderable. Over this period, the system can reasonably be expected to experience increasing demand in line with a growing population and economy, with much of this demand taking place on urban segments of the Interstate System that are already heavily used.

A safe, reliable, resilient, and well-functioning Interstate System is almost certain to be needed to accommodate traffic growth over the next two decades and beyond, but is plausibly even more critical to ensuring that the benefits of technological advances can be exploited and vulnerabilities to climate change can be minimized over the longer term. A medium-term investment strategy—one targeted to the more foreseeable future of the next two decades—that renews and modernizes the system's aging and worn pavements and bridges and aligns and allocates capacity in anticipation of growing traffic demand can be viewed as fundamental to the longer-term interest of preparing the Interstate System for the opportunities and challenges deeper into the century.

The focus of this chapter is on defining the core elements—and associated investment requirements—of a 20-year strategy for renewing and modernizing the Interstate System under various, historically informed assumptions about plausible traffic growth. The average annual investment required for some of these elements can be approximated using available modeling systems, while that for other elements cannot be quantified as readily because of a lack of data, modeling capabilities, and other relevant information about the specific actions required to address them. In this regard, the dollar estimates presented herein can be viewed as minimums. Although the explanation of how these estimates were calculated consumes much of the discussion in this chapter, the investments in areas identified in the chapter that are unaccompanied by annual spending estimates—such as rebuilding interchanges and increasing system resilience—should not be viewed as being of lower priority.

GENERAL APPROACH FOR ESTIMATING INVESTMENT NEEDS

At a Glance

- Standard Federal Highway Administration (FHWA) models for estimating highway and bridge investment needs are used as the main basis for approximating the investment levels required to renew and modernize the Interstate Highway System over the next 20 years, assuming alternative rates of traffic growth.
- Whether an investment is categorized as "needed" depends on the highway condition and performance outcomes that are desired or considered acceptable by decision makers. While such outcomes are subjective, the estimates developed in this chapter are derived from modeled benefit-cost calculations—the approach recommended by Congress in requesting this study.
- The estimates presented herein are intended to provide general guidance to decision makers on the magnitude of investments required over the next 20 years.

To define the core needs for renewal and modernization of the Interstate Highway System over the next 20 years, and to approximate the average annual spending required to meet those needs, the committee employed the Federal Highway Administration's (FHWA's) standard modeling tools, supplemented by other information and methods when the models were judged to be insufficient. This approach is consistent with the legislative request for the study, in which Congress recommended the use of the analytic methods proposed in the report of the National Cooperative Highway Research Program (NCHRP) Project 20-24(79), *Specifications for a National*

Study of the Future 3R, 4R, and Capacity Needs of the Interstate System (Miller et al. 2013). That report recommends use of the FHWA's modeling systems for highway and bridge investment needs (described below), supplemented by information derived from case studies of Interstate projects, for predicting investment levels needed to attain prescribed performance and condition outcomes under different assumptions about future Interstate traffic growth.

The term "investment needs" warrants explanation as used in the context of this report. Whether an investment is "needed" depends on what outcomes one desires or considers acceptable, such as how much pavement smoothness is desirable or how much traffic delay is acceptable. Because determinations of outcomes that are desirable or acceptable to the public are subjective, it is obviously not possible to make definitive estimates of "needed" levels of public spending. However, Congress specifically directed the committee to conduct its analyses and use its judgment to recommend investment levels informed by the methodology proposed in the NCHRP report. As noted above, a key component of that proposed methodology is FHWA's modeling tools for highway investment needs—the Highway Economic Requirements System (HERS) and National Bridge Investment Analysis System (NBIAS). FHWA uses the models in its biennial *Conditions and Performance* (*C&P*) report to Congress (FHWA 2016a). The *C&P* report thus provides Congress with approximations of the overall investment that will be needed over a period of time to achieve certain condition and performance outcomes and enables assessment of how alternative investment levels will affect these outcomes, or vice versa.

The approach used in this chapter for estimating 20-year investment levels is a derivative of the methodology proposed in the NCHRP report. The committee developed these estimates using the recommended models by applying a range of projected rates of growth in motor vehicle travel. The results are limited by the coverage and design of the databases used in the models to depict the current condition and performance of the highway system, as well as a number of other factors described below. Nevertheless, the committee concluded that HERS and NBIAS can be informative regarding the magnitude of investments that will be required to renew and modernize the Interstate System over the next 20 years, and that the methodologies and output of these models have the important advantage of being familiar to decision makers, including Congress.

Because HERS and NBIAS are designed to consider standard options for improving pavements and bridges, they need to be supplemented with other data and tools to enable a fuller consideration of improvements that can be made to the system. The chapter examines some additional improvement options applicable to the next two decades, such as the construction of special-purpose tolled and truck-only lanes. The chapter also contains a brief discussion of the improvements that will eventually be needed to add resilience to the system and modify its length and scope to accommodate a changing geography of user demand, a discussion that is necessarily limited because the committee could find no reasonable basis for estimating the cost of making these improvements over the next 20 years.

Before considering the annual spending that will be needed for Interstate System renewal and modernization over the next two decades, the chapter considers spending on the system over the past two decades as context for the nature and scale of the investment that lies ahead. This review is also important for understanding the starting point for future investments, which includes a backlog of highway and bridge repair, replacement, and capacity expansion and management needs.

RECENT INTERSTATE CAPITAL SPENDING AND THE INVESTMENT BACKLOG

At a Glance

- In 2014, $25 billion, including both state funds and federal aid, was expended on the Interstates. Of this amount, $20 billion was allocated to improvements to pavements and bridges; $2.2 billion to new construction and relocation projects; $1 billion to major widening projects; and the remainder to traffic operation and control systems and safety and environmental enhancements.
- While states have gradually increased their spending on pavement surface repairs and rehabilitation, spending on full reconstruction of pavement foundations has remained relatively unchanged despite a growing inventory of pavement structures that have exceeded their original design lives.
- Even if future traffic volumes and loadings grow modestly, tens of billions of dollars in pavement renewal and modernization work that has been deferred will be coming due over the next 20 years.

In 2014—the most recent year for which complete and detailed capital spending data are available—states spent $25 billion, including their own funds and federal aid, on the Interstates. Of this amount, $20 billion went to improvements to existing pavements and bridges, $2.2 billion to newly constructed highways and bridges, and $1 billion to major widening projects. The remaining spending, recorded as capital investments, funded traffic operations and control systems and safety and environmental enhancements (FHWA 2016b, Table SF-12A). These figures do not include spending on day-to-day maintenance activities, such as snow and ice control, pothole repair, and mowing of medians and other rights-of-way. These latter expenditures are not classified as capital spending and are not considered in this report, except to recognize that such maintenance activity and its costs are affected by capital investment choices.

Total capital expenditures on the Interstates in 2014 are largely indicative of the magnitude of spending over the previous two decades, but with some exceptions. Figure 5-1 shows state expenditures (in 2016 dollars) on pavement-related projects for the 17-year period 1998–2014 as recorded by FHWA. (When this report was being developed the most recent complete data on spending was for 2014.) Evident in this figure is a large increase in spending in 2011, the result of the one-time augmentation of federal-aid highway funding authorized under the 2009 American Recovery and Reinvestment Act. Also evident, however, is the gradual increase since 2004 in spending on pavement rehabilitation, which includes surface repairs, resurfacing, and similar restoration and preservation work.

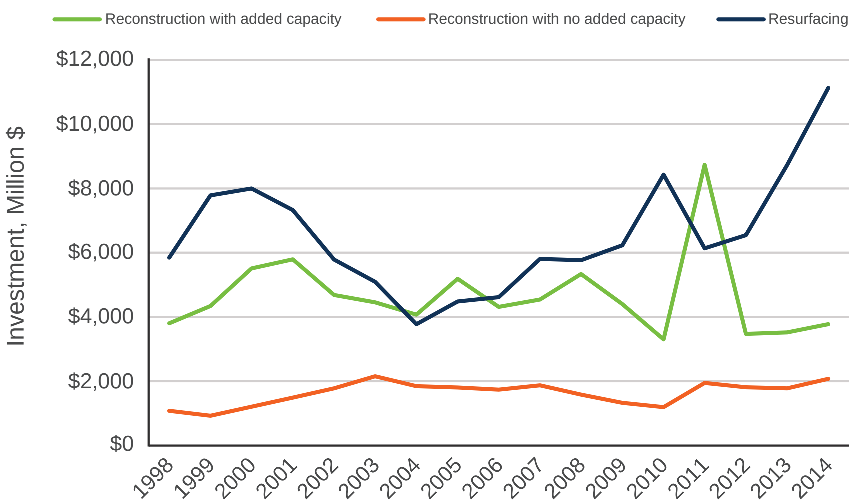

FIGURE 5-1 State investments in pavement reconstruction, resurfacing, rehabilitation, and restoration of Interstate highways, including federal aid (in 2016 dollars, using gross domestic product [GDP] price deflator).
SOURCES: FHWA 1999–2015, 2016b.

The most common pavement rehabilitation procedure is to replace the surface course through resurfacing, which is typically done with an asphalt overlay.[1] In 2014, this spending category accounted for about two-thirds of state pavement-related expenditures, compared with previous highs of 57 percent in 2000 and 63 percent in 2010. Most of the increase in total pavement-related expenditures during the 17-year period, which have grown in real terms by 50 to 70 percent since the mid-2000s, stemmed from increases in spending on surface treatments. By comparison, spending on pavement reconstruction—including projects with and without accompanying capacity additions—remained relatively unchanged over this period. Pavement reconstruction goes beyond adding overlays and fixing surface deficiencies, and almost always involves replacing the pavement structure with new materials. This spending category includes, but does not identify the amount spent on *full-depth* reconstruction, which involves replacement of the pavement surface and base and stabilization or regrading and compaction of the subbase.

Figure 5-2 shows annual state capital expenditures over the same 17 years for Interstate bridge work. Here again, the sudden spending increase due to the American Recovery and Reinvestment Act can be seen in

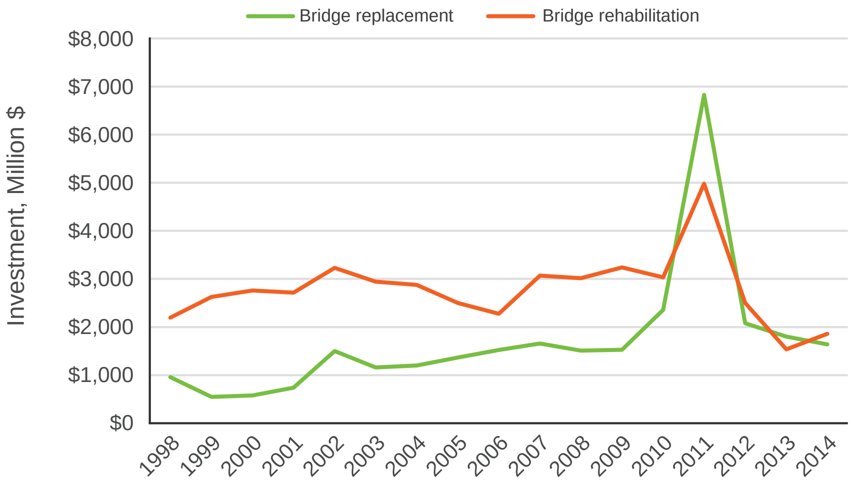

FIGURE 5-2 State investments in Interstate highway bridge replacement and rehabilitation, including federal aid (in 2016 dollars using gross domestic product [GDP] price deflator).
SOURCES: FHWA 1999–2015, 2016b.

[1] Typically this treatment would include replacement of spalled or malfunctioning joints, substantial pavement stabilization prior to resurfacing, grinding or grooving of rigid pavements, and replacement of deteriorated material (see FHWA n.d.-a, Chapter 12).

2011. Otherwise, however, annual bridge spending in real terms was stable throughout the decade preceding 2014. Finally, Figure 5-3 shows capital spending on new highway and bridge construction during the same 17-year period. In this case too, the trend has been one of flat or slightly declining annual spending, at least when investment levels from the 2010s are compared with those from a decade earlier.

Despite this capital spending on the Interstates, which has averaged about $20 billion per year (in 2016 dollars) since 1998, the system is not in pristine condition, and investments deferred in the past will need to be made in the future. These future investments will be accompanied by required spending for repair, reconstruction, and expansion resulting from the system's ongoing aging, wear, and use. In its 2015 *C&P* report, FHWA calculated that in 2012, a $145 billion backlog of investment needs would need to be liquidated to bring the system up to economically justified levels of condition and performance. Table 5-1 provides a detailed breakdown of this estimate and updates the calculations to 2016 based on system condition and performance data for that year as derived from FHWA's Highway Performance Monitoring System (HPMS) and National Bridge Inventory (NBI). The 2016 calculations suggest that the pavement backlog decreased, presumably in response to recent increases in state pavement investments shown in Figure 5-1. The bridge backlog, however, increased, along with the backlog of needed capacity additions.[2]

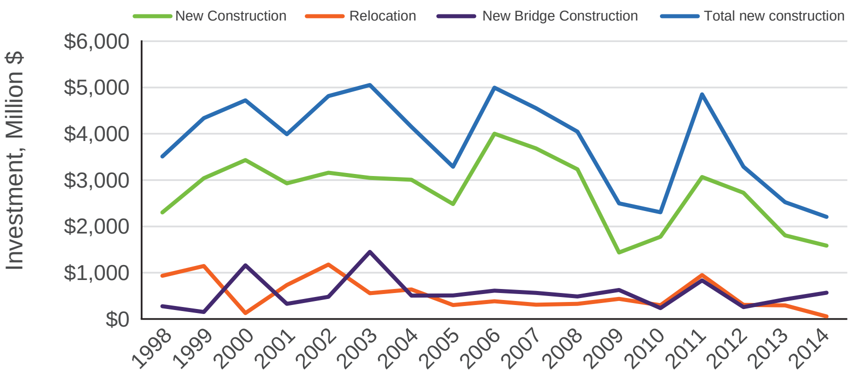

FIGURE 5-3 State investments in new construction and relocation of Interstate highways and bridges, including federal aid (in 2016 dollars using gross domestic product [GDP] price deflator).
SOURCES: FHWA 1999–2015, 2016b.

[2] The increase in bridge backlog from 2012 to 2016 demonstrates that a linear increase in annual investment does not result in a linear improvement in the level of backlog from year to year over that same period. This a reflection of variations in age, condition, and rates of deterioration among the bridges in the inventory.

TABLE 5-1 FHWA Estimated Interstate Investment Backlog

	Rehabilitation[a]			Capacity	
Year	Pavements	Bridges	Total	Expansion[b]	Total
2016	$50B	$44B	$94B	$55B	$149B
2012	$62B	$40B	$102B	$43B	$145B

[a] For pavements, rehabilitation involves resurfacing and surface layer reconstruction.
[b] In the context of analysis of investment needs, system expansion refers to added lanes.
SOURCE: FHWA's (2016a) *C&P* report, based on 2012 data and updated to 2016 using that year's data and the same methods.

Although the types of work required to reduce these backlogs have changed somewhat over time, the total has remained at about $150 billion. As will be discussed below, this figure does not fully account for the spending that will be needed to reconstruct aging and deteriorating pavement foundations, whose condition is not tracked by HPMS.

Prospectively, it would be unrealistic to believe that an Interstate highway investment strategy for the next 20 years could reduce this backlog quickly. In fact, much of any future spending to renew and modernize the Interstate System will have its origins in past decisions to defer reconstruction work and capacity additions. Future growth in traffic demand and its impacts on the system's pavement condition and operating performance will be an important determinant of future investment needs, but not the only determinant. Indeed, even if traffic volumes and loadings grow modestly, it can be said with reasonable assurance that tens of billions of dollars in renewal and modernization work deferred over the past several decades will be coming due.

MODELING TOOLS AND ASSUMPTIONS USED IN ESTIMATING FUTURE INVESTMENT NEEDS

Modeling Capabilities and Limitations

HERS and NBIAS can be used to assess investment needs from more than one perspective. They can, for instance, answer such questions as what level of spending is required annually to maintain and improve pavement and bridge conditions and operating performance over a period or what levels of system condition and operating performance can be achieved over a period with a given amount of spending. To answer such questions, HERS and NBIAS monetize the benefits and costs of a set of candidate improvements and calculate their impacts on aspects of system condition and performance.

Box 5-1 lists the categories of benefits and costs monetized in HERS, as well as the measures that are used to calculate condition and performance. Monetized benefits include impacts on motorists (e.g., travel time, vehicle operating costs, safety) and society (e.g., emissions), as well as savings in highway agency maintenance and operating budgets. Monetized costs comprise exclusively expenses incurred by agencies in implementing an improvement, including acquiring right-of-way and hiring contractors to perform the work. Condition and performance measures include indicators of pavement surface condition (e.g., smoothness or roughness) and operating performance (e.g., ratio of peak volume to capacity, absolute delay).

BOX 5-1
Costs, Benefits, and Condition and Performance Categories in the Highway Economic Requirements System (HERS)

Benefit Categories Considered

- Changes in user travel time costs
- Changes in vehicle operating costs (fuel, oil, tires, maintenance, depreciation)
- Changes in crash costs
- Changes in pollution costs (combined costs of carbon monoxide [CO], nitrogen oxide [NOx], particulate matter [PM_{10}], volatile organic compounds [VOCs], sulphur oxides [SO_X], and road dust)
- Changes in agency highway maintenance and operations investments

Cost Categories Considered

- Initial right-of-way acquisition
- Construction costs

Condition and Performance Categories (before and after improvements)

- Measures of congestion (ratio of peak volume to capacity)
- Speed by segment and averaged by functional class
- Delays
- Pavement condition indices
- Miles of selected roadway improvements
- Deficiency ratings for geometric features
- Crash rates
- Fatalities

SOURCE: TRB Transportation Economics Committee n.d.

Clearly such a limited set of monetized benefits and costs cannot account for all societal and economic impacts and their incidence, nor can the measures of system condition and performance include all criteria that may be of interest to highway users and policy makers. Furthermore, neither HERS nor NBIAS considers all types of potential highway and bridge improvements or the broader set of options at the disposal of policy makers for achieving a specific desired outcome. Some of the missing options may be more cost-beneficial than those considered in the models. Examples of options not considered to address capacity-related deficiencies include building an entirely new highway; adding high-occupancy toll (HOT) lanes or other forms of managed lanes; implementing reversible lanes; instituting policies that would reduce the demand for Interstate travel, such as land use restrictions; and investing in public transit to accommodate growing demand on the existing highway system. Similarly, a range of safety improvements are not considered. Safety is considered to be improved in HERS only if wider lanes, wider shoulders, and curve and grade flattening are introduced. HERS does not consider removing unsafe geometric features, such as short acceleration and deceleration ramps. With regard to pavement condition, a highway improvement that is not considered by HERS is the option of full-depth pavement reconstruction.

Additionally, the HPMS database used by HERS to ascertain current system condition and performance consists of a large sample of individual highway segments. Accordingly, when HERS calculates the benefits and costs of an improvement, it does so for each segment independently rather than over a longer route or corridor. The same is true for NBIAS, which considers the benefits and costs of each bridge improvement in isolation. The models, therefore, cannot capture the upstream or downstream "coupling" effects of changes to a given highway segment or bridges.

Finally, for both HERS and NBIAS, demand is an exogenous input not derived within the models. The user specifies the level of vehicle-miles traveled (VMT) growth, for instance, to estimate the future need for capacity-related improvements. This means the models do not account fully for the effect of capacity changes on VMT itself. Changes in travel behavior in response to capacity additions are commonly referred to as "latent" and "induced" travel demand. The former term is used most commonly to describe the increase in traffic volume over what otherwise would have been expected from improvements to a facility as travelers take advantage of the faster travel speeds. For instance, travelers may divert from other routes or transit. Moreover, the improved traffic conditions (e.g., travel speeds and reliability) resulting from the increase in highway capacity may allow existing travelers to make additional and longer trips. Over the longer term, increased highway capacity may improve the accessibility of a region, stimulating economic and land development and thus encouraging the generation of new trips, or inducing demand. Conversely, as congestion increases when capacity becomes constrained and is not increased, some travelers may change their behavior to avoid the resultant delay, in which case the overall effect will be to suppress travel demand to a degree. In short, any capacity increase (or reduction in the cost of traveling on the highway) will increase travel, while any capacity reduction (or increase in the cost of traveling on the highway) will decrease travel.

HERS contains demand elasticities as a way to control partially for the effects of supply conditions on demand.[3] Improved facilities are assumed to experience a bump in VMT growth rates that will offset some of the delay savings, while unimproved facilities are assumed to experience suppressed VMT growth in response to increasing levels of congestion. The latter feature prevents unconstrained traffic growth in the face of congestion that would otherwise be expected to impede traffic volumes. Many metropolitan planning organizations and state departments of transportation have developed travel demand forecasting (TDF) models that address, at least partially, the interaction between travel demand and system supply conditions. These TDF models usually estimate the VMT effects from short-term behavioral changes by accounting for changes in routes, modes, and destinations. Some more sophisticated models also account for shifts in travel times. Rarely, however, are the longer-term induced-demand effects addressed by the models because of the difficulty of predicting how changes in supply will lead to changes in land use and the resulting changes in traffic.

The committee concluded that existing TDF models do not offer the national- or regional-level prediction capabilities needed to assess system-level impacts from Interstate investments. Importantly, these models, like HERS, could not be used to account for the redistribution of traffic on the system or other travel routes and modes. Because there are no existing tools with which to analyze these demand responses at the transportation network level for the entire country or regionally, the only alternative was to consult the recent history of travel behavior as indicated by past VMT growth rates to develop a reasonable range of future VMT growth rates to apply to the HERS and NBIAS models. The choices of VMT growth rates are discussed next. The limitations of HERS and NBIAS, as discussed in this section, are summarized in Box 5-2.

[3] Demand elasticity refers to the percentage change in travel demand divided by the associated percentage change in the price of travel, which can be measured in terms of travel time or the total cost associated with travel.

BOX 5-2
Applicability of Highway Economic Requirements System (HERS) and National Bridge Investment Analysis System (NBIAS) Modeling Systems to This Study

The legislative request for this study called for the use of the Federal Highway Administration's (FHWA's) HERS and NBIAS models to estimate the investment required to restore the Interstate Highway System to its premier status in the country's transportation system. The committee understood that these two models were designed largely for the purpose of informing Congress's decisions about future investment needs for the federal-aid highway program in the aggregate, as opposed to informing decisions about investments in individual assets (which are made by states). Although the committee identified limitations in the two models for the specific purposes of this study, as summarized below, it concluded that those limitations are manageable, and that alternative modeling capabilities with greater relevance do not exist and could not be developed specifically for this study.

Both HERS and NBIAS are built off databases that sample (Highway Performance Monitoring System [HPMS]) or survey (National Bridge Inventory [NBI]) the current condition and performance of segments and structures on the Interstate System. Having such baseline information on current conditions and performance levels is essential for testing the effects of different levels of spending on different types of highway improvements under changing traffic levels. A limitation of HERS in this respect is that HPMS, the database on which it is based, does not contain information on the condition and performance of Interstate highway interchanges and pavement foundations, which are major cost components of the system.

Another limitation of the models is that they assume that rates of traffic growth are largely exogenous to the models' output; the model user must specify traffic growth rates. Ideally, the traffic growth rate and pattern would respond to the predicted changes in system condition and performance and lead to changes in traffic extending beyond the improved segment. HERS and NBIAS lack this capability to model responses over a system and with feedback, which can be a particular problem for estimating effects over longer time horizons when demand and supply conditions are more variable and interact.

The models test the effects of a limited set of improvements. They cannot be used to assess the impacts of a new facility, and they do not consider all system pricing; technology deployment; and configuration options available, such as the conversion of lanes for special purposes (e.g., high-occupancy vehicle [HOV] and truck-only service). The models calculate a limited set of benefits and costs of investments (outlay expenses and benefits and costs arising from changing conditions), rather than societal benefits and costs. As the unit of interest (e.g., all downtown freeways in large metropolitan areas) becomes more granular, the models use fixed parameters that may not be applicable, and the outcomes are not sufficiently context-specific.

In the investment needs analyses presented in this chapter, these modeling limitations are noted, and some cases are compensated for.

Assumed Future Rates of Growth in VMT

To use HERS and NBIAS to make estimates of Interstate investment needs, it is necessary to specify future rates of VMT growth as inputs to the models. While the current state of the Interstate Highway System is a major determinant of future investment needs (as noted earlier in discussing the investment backlog), future traffic volumes will add to these needs as a consequence of added pavement and bridge loadings and wear and new capacity demands. Because neither HERS nor NBIAS differentiates between the traffic growth rates of passenger cars and trucks on pavement and bridges or their relative loadings—which is a notable deficiency of the models—only a composite rate of growth in VMT (combined passenger car and truck travel) can be specified.[4] Even if the models did allow for more granular VMT specification—such as for local, interregional, and longer-distance Interstate trips—the data available for developing such input are limited. For example, the U.S. Department of Transportation's (U.S. DOT's) American Travel Survey, the only national-level database on longer-distance travel that includes highway trips, has not been updated in more than 20 years.

As discussed in the previous chapters, highway planners have had mixed experience forecasting VMT. Planning of investments in long-lived transportation infrastructure, however, requires VMT forecasting. However, even for a period of 20 years, such forecasting presents challenges. The magnitude, location, and timing of changes in travel demand will depend on a host of factors related to changes in the population and economy, how travelers respond to congestion and the supply of new capacity, whether new capacity is restricted to specific users, and the availability of options other than Interstate travel. Transportation agencies, especially in urban areas, may substitute more active operations and demand management measures, such as congestion tolling, which will affect travel demand levels. Although connected and automated vehicles are likely to have limited effects on travel demand in the nearer term, some impacts may be observed in 15 to 20 years.

Informed by the resource paper prepared by Polzin for this study (see Appendix C), the conclusion reached in Chapter 4 is that VMT growth ranging from 0.75 percent to 2 percent per year is a reasonable expectation

[4] Although the modeler cannot specify different VMT growth rates for passenger and freight vehicles, both models account for passenger and truck weights and loadings when performing impact analysis. The HPMS database, for example, includes truck percentages for single units and combinations for every highway section, and HERS assumes typical loading patterns for trucks as well as for passenger vehicles.

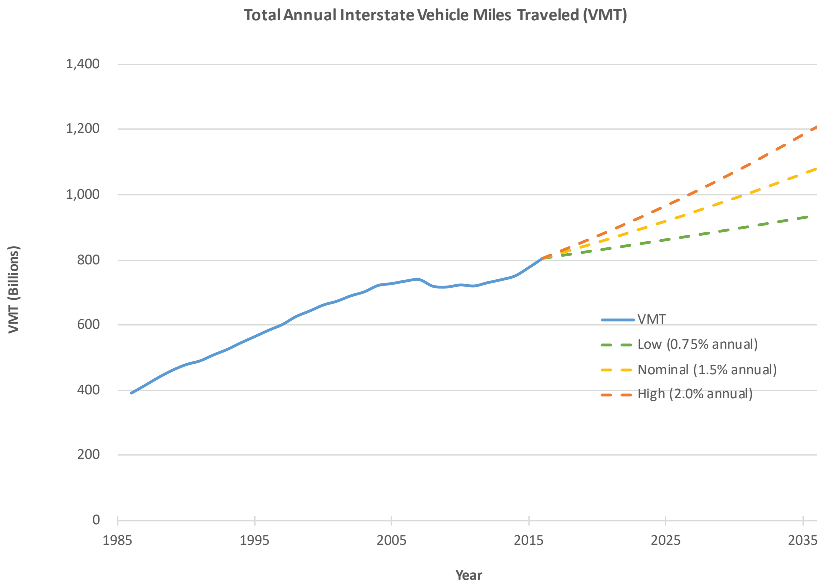

FIGURE 5-4 Total annual Interstate vehicle-miles traveled, historic since 1985 and projected after 2016, based on assumed growth rates.
SOURCE: FHWA 2017.

for the next 20 years—comparable to trends observed in recent decades and corresponding to the country's projected population gains, factoring in expected economic growth. This report uses a midrange or "nominal" VMT growth rate of 1.5 percent, with low and high excursions of 0.75 and 2.0 percent, respectively, which the committee believes to be reasonable lower and upper bounds (see Figure 5-4). The lower bound might be more representative of future experience in locations where steps are taken to manage demand more aggressively, such as through congestion pricing on heavily trafficked urban routes. The higher bound might be more representative of future experience in locations where chronic congestion is not a problem today but where travel demand is growing because of population increases and economic development, such as in emerging metropolitan areas.

Methods for Calculating Needed Investments

As discussed above, HERS and NBIAS calculate the costs and benefits of Interstate improvements assuming different rates of VMT growth that place demands on the system. For example, in HERS the benefits of a candidate improvement are measured in terms of the savings to users (lower travel times, improved safety, and reduced vehicle operating costs, such as fuel, tire, and vehicle depreciation costs); to highway agencies (lower maintenance costs); and to society (savings in the costs associated with emissions). These monetized benefits are then compared with the outlays required for making the improvement, computing a benefit-cost ratio (BCR). Generally, when the BCR exceeds 1, the improvement is deemed to be cost-beneficial. However, the models also allow the user to specify a BCR that is lower or higher as the criterion for choosing an improvement. A higher BCR threshold might be selected, for instance, when there is a limited budget for making improvements.

The committee concluded that a BCR of 1 should be the basis for its nominal estimates of investment needs. As explained in Chapter 1, when Congress asked for estimates of the resources needed to restore and upgrade the Interstate System it did not specify a budget constraint. However, recognizing that the funding available to invest in the system may be limited, the committee also computed the spending levels that would be required to make all improvements that meet a higher BCR threshold of 1.5. In each case, the models can be used to show how the investments would affect certain aspects of system condition, such as pavement smoothness and person-hours of delay.

Note that the outcome of interest from investments is not necessarily a "state of good repair." While this term has become popular in transportation asset management, what constitutes a "good" condition remains ambiguous. Inasmuch as the pursuit of such a state implies that all system deficiencies should be corrected, the result can be overinvestment in work that does not produce net benefits. The presumption here is that policy makers seek investments that promise positive net benefits.

Figure 5-5 summarizes the various components of the modeling approach in a graphical format. The use of another tool to supplement the HERS and NBIAS models, the Pavement Health Track (PHT) tool, is explained in the next section, which describes how the committee estimated pavement and bridge rehabilitation and reconstruction needs.

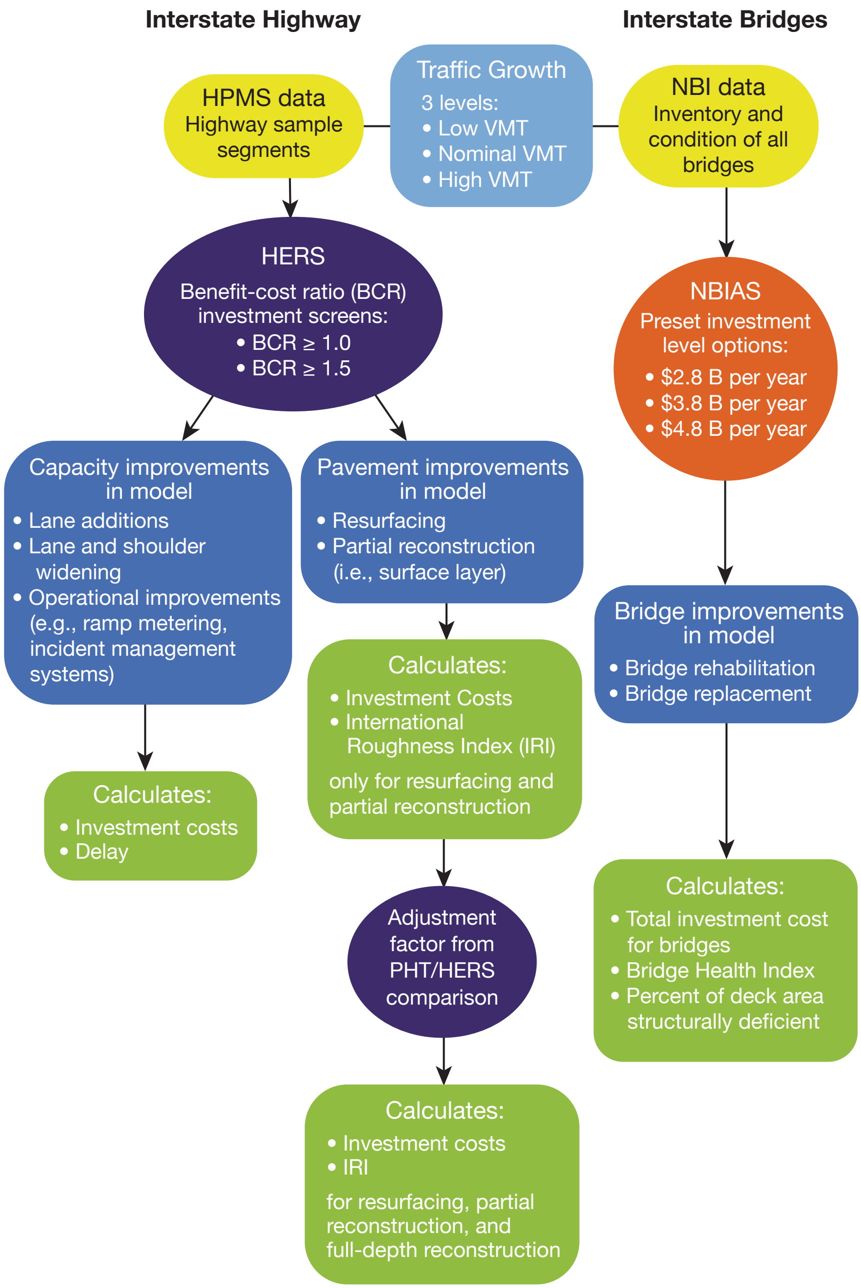

FIGURE 5-5 Schematic of application of HERS and NBIAS models for calculating Interstate Highway System investment needs for the next 20 years.

ESTIMATING 20-YEAR PAVEMENT AND BRIDGE RENEWAL INVESTMENT NEEDS

At a Glance

- Applying a strategy that invests in all cost-beneficial improvements, pavement investment needs average on the order of $27–$32 billion annually over the next 20 years (roughly double the current spending levels), based on assumed growth in VMT ranging from 0.75 to 2.0 percent per year. This investment level includes the cost of fully reconstructing Interstate pavements and their foundations.
- Modeling suggests that states are already devoting sufficient funds to continuing to maintain and improve Interstate bridges. Somewhat higher annual investments (~25 percent) than are made today would lead to further improvements in the physical condition of these bridges by reducing structurally deficient deck area; however, this deficiency is generally considered to be a serviceability or ride quality issue rather than a safety concern. An investment level averaging $4 billion per year—similar to what is being spent today—is a reasonable approximation of the Interstate System's bridge investment needs for the next 20 years.

This section presents estimates of the investment required over the next 20 years to renew the Interstate's pavements and bridges, which includes reducing the backlog of deferred investments, and to address forthcoming needs arising from the system's continued aging and future use. These estimates were derived largely from HERS and NBIAS, employing the assumptions discussed above.

Pavement Investment Needs

As discussed earlier, HERS, FHWA's primary model for estimating national pavement investment needs, uses information about the current Interstate Highway System's condition and performance from FHWA's HPMS database (FHWA n.d.-d). When HERS is programmed with a specific rate of VMT growth, it computes the impact of the resulting traffic volumes and loadings on the system's physical condition and operating performance and generates a candidate set of standard improvements to highway width, pavement, and alignment, as well as additional lanes. The algorithms then calculate which improvements should be made according to the user-defined BCR.

As noted previously, a significant shortcoming of HERS for assessing pavement investment needs is that it does not consider all pavement conditions and types of improvements, partly because of limitations in the model's data source, HPMS. The condition of pavements is recorded in HPMS mainly according to a measure of ride quality, the International Roughness Index (IRI), which does not account for structural condition. Pavement improvement options in HERS are thus limited to surface treatments or partial reconstruction of top layers, which can be characterized only as rehabilitation or preservation work.

As discussed in Chapter 3, the service life of pavements can be extended through such rehabilitation activity as resurfacing, but eventually the pavements and their foundations will deteriorate to a point where surface repairs are no longer effective, and the entire structure needs to be replaced from the subbase up. The timing of that eventuality depends on a number of factors, including design choices (e.g., pavement thickness, base depth), the quality of the original construction and materials, traffic loadings, and environmental factors (TRB 2007). One would expect, however, that states

BOX 5-3
Estimated Benefits and Costs of Including Condition-Based, Full-Depth Pavement Reconstruction in Analysis of Interstate Investment Needs

The present study used the Pavement Health Track (PHT) analysis tool, in addition to the Highway Economic Requirements System (HERS), to estimate Interstate highway reconstruction needs. Like HERS, PHT draws on pavement segment data from the national Highway Performance Management System (HPMS) database to screen for deficient segments, identifies feasible improvement options, selects an optimal option based on benefits and costs, and ultimately estimates costs of improvement. In contrast to HERS, however, PHT permits selection of multiple pavement condition metrics (e.g., fatigue cracking, rutting, faulting), including use of the International Roughness Index (IRI) to screen for deficiencies. The presence of fatigue cracking—a good indicator of full-depth cracking in all types of pavements—was used in this study as an indicator of structural inadequacy.

A comparative analysis of projected improvement needs for a representative sample of more than 1,600 HPMS segments was performed using PHT together with HERS. The purpose of this analysis was to develop an adjustment factor that, when applied to the HERS output, would be indicative of the pavement improvements required (i.e., full-depth reconstruction or surface treatment).

The comparative analysis was conducted for the following two scenarios:

- Scenario 1: For this scenario, a needs projection from PHT and HERS based on the IRI only was developed to provide a point of reference for comparing differences between key PHT and HERS outputs and making suitable calibration adjustments to PHT to ensure similar outcomes.

will find it necessary to increase spending on reconstruction of Interstate pavements over the next decade and beyond because much of the system's original foundation will not have been rebuilt.

The inability of HERS to estimate full-depth reconstruction needs is problematic for estimating longer-term pavement investment needs. Thus to obtain a better understanding of the full-depth reconstruction that will be needed and its cost, the committee made use of FHWA's PHT analysis tool. PHT, like HERS, uses HPMS data, but it screens more closely for signs of foundation deterioration by identifying pavement deficiencies based not only on surface smoothness measures (i.e., IRI) but also the observed presence of fatigue cracking. PHT then determines that some pavement deficiencies that would be identified by HERS as merely demanding rehabilitation should be treated in other ways, including full-depth reconstruction.

The application of PHT to a sample of pavements in HPMS, as described in Box 5-3, allowed for the committee to develop an adjustment factor to apply to the HERS-derived estimates of pavement rehabilitation needs. In essence, the additional consideration of fatigue cracking suggests

- Scenario 2: For this scenario, only PHT runs were completed using both IRI and fatigue cracking for deficiency screening and an expanded set of treatment options typical of maintenance work ordering for pavements.

The results of Scenario 1 indicate close agreement between key PHT and HERS outputs (average posttreatment IRI improvement and average benefit-cost ratio for the more than 1,600 HPMS segments analyzed), implying that no calibration of PHT outputs was required and providing a sound basis for investigating the combined circumstance of Scenario 2. The results of the Scenario 2 analysis show that the inclusion of full-depth cracking along with IRI enhances the ability to (1) identify pavement structural deficiencies and (2) select more life-cycle-optimized improvement options. The major conclusion is that when fatigue cracking is considered in maintenance decisions, the number of sections requiring planned maintenance actions and the associated costs increase significantly, whereas the number of sections requiring corrective maintenance, such as patching, decreases.

In summary, compared with Scenario 1 (IRI only), the additional consideration of fatigue cracking in maintenance decisions results in an overall increase in forecast improvement costs by a factor of about 2.0 (i.e., 100 percent higher). Simultaneously, benefits in terms of benefit-cost ratio (BCR) and extended pavement life are significantly higher than those accrued when IRI alone is used as a deficiency screening factor and criterion for postmaintenance restoration condition. Thus, use of this method makes it possible to obtain a first-order estimate of the increased costs and benefits that result when condition-based, full-depth reconstruction is considered as an option in the needs evaluation. A more robust analysis for all HPMS segments (beyond the scope of this study) is highly advisable to determine whether HERS is significantly underestimating pavement reconstruction needs on sections of the Interstate Highway System not previously reconstructed.

that the HERS results should be adjusted upward by a factor of 2. In the sections that follow, pavement investment needs are calculated first using HERS only, and second by applying the PHT-derived adjustment factor. Because they include needed reconstruction work, the second set of estimates are considered to be more indicative of future investment needs.

Rehabilitation-Only Estimates Using HERS

Table 5-2 displays the HERS-computed annual investment that would be needed for pavement rehabilitation over the next 20 years under the high, nominal, and low VMT forecasts, in each case according to the two BCR investment criteria (BCR ≥1 or BCR ≥1.5). The table also shows the effect of applying these criteria on the share of Interstate pavements in poor condition, as measured by surface roughness (i.e., IRI). Rehabilitation spending in all cases would go up with increases in the rate of VMT growth. Investing in all improvements having a BCR ≥1 would keep the share of pavements with poor surface conditions at the current 2 percent level at the end of the 20-year period. This strategy would require an annual investment of about \$13–\$17 billion depending on traffic growth rates. Applying a higher BCR of 1.5, as might be pursued under strict budget limitations, would reduce rehabilitation spending by about one-third, but pavement surface conditions would degrade significantly.

Reconstruction and Rehabilitation Estimates Using HERS in Conjunction with PHT

In recent decades, states have been designing and building Interstate pavement surfaces and foundations to achieve longer service lives (TRB 2007).

TABLE 5-2 Annual 20-Year Investment for Alternative Pavement Rehabilitation–Only Investments Under Different Assumed Rates of Growth in Vehicle-Miles Traveled (VMT), Showing the Share of Pavements with Poor Surface Condition at the End of the 20-Year Period (in parentheses)

	Annual VMT Growth Rate		
	Modest	**Nominal**	**High**
Investment Criteria	0.75%	1.5%	2.0%
BCR ≥1.0	\$13.3B (4%)	\$14.4B (4%)	\$16.8B (4%)
BCR ≥1.5	\$9.0B (6%)	\$9.9B (7%)	\$10.5B (7%)

NOTES: Results from analysis using the Highway Economic Requirements System (HERS). BCR = benefit-cost ratio.

However, the amount of mileage that has actually been impacted by these investments during highway reconstruction projects is not known. Whereas states are required to report to FHWA their total annual expenditures on Interstate reconstruction projects, they are not required to report the number of miles or lane-miles involved. Because the amount of reconstructed Interstate mileage is not known, at least at the national level, it is difficult to know how much of the total system has a foundational footprint whose condition can be considered good. For the Interstate System's first 20 to 40 years, however, relatively little was spent on reconstruction (as discussed in Chapter 3). Because so much of the Interstate System was built in the 1960s and early 1970s with 20-year design lives, it is reasonable to expect that a large share of the original pavement foundation remains in place and is due, or long overdue, for complete replacement.

Table 5-3 presents the results of the combined HERS-PHT analysis under the same set of VMT growth rates and BCR investment criteria presented in Table 5-2. These results suggest that pavement investments over the next two decades will need to be approximately twice as high as those calculated by HERS of Interstate foundations that will need complete rebuilding rather than rehabilitation only. If nominal VMT growth (1.5 percent annually) is assumed and improvements having BCRs of 1 or higher are chosen, the annual investment in pavement is on the order of $29 billion per year. Table 5-3 shows how these rehabilitation and reconstruction investment needs do not change much across the three different scenarios of growth in VMT.

The reason the HERS-PHT estimates are significantly higher than the estimates derived from HERS alone is that reconstruction is much more expensive than simple rehabilitation. Case studies of Interstate pavement reconstruction projects undertaken for this study (see Appendix I) indicate

TABLE 5-3 Annual 20-Year Investment Levels for Both Pavement Rehabilitation and Reconstruction Investment Under Different Assumed Rates of Growth in Vehicle-Miles Traveled (VMT), Showing the Resultant Share of Pavements with Poor Surface Condition at the End of the 20-Year Period (in parentheses)

	Annual VMT Growth Rate		
	Modest	**Nominal**	**High**
Investment Criteria	0.75%	1.5%	2%
BCR ≥1.0	$26.6B (4%)	$29.0B (4%)	$31.6B (4%)
BCR ≥1.5	$18.8B (6%)	$19.8B (7%)	$21.0B (7%)

NOTES: Based on analysis conducted using the Highway Economic Requirements System (HERS) and Pavement Health Track (PHT). BCR = benefit-cost ratio.

that the average investment is about $2.8 million per lane-mile on a rural Interstate and about $5 million per lane-mile on an urban Interstate (without adding any improvements beyond pavement reconstruction). The 20-year investment in reconstructed pavements, however, should lead to greater serviceability and lower resurfacing needs in decades beyond the 20-year period considered herein.

Summary Assessment of Pavement Investment Needs

The committee is reluctant to rely on the HERS-derived estimates of pavement investment needs because the Interstates are overdue for extensive pavement foundational work given their age. Although the combined PHT-HERS method yields a rough approximation of investment needs, the committee believes it is more realistic in generating estimates of spending needs because it includes full reconstruction. Using this method, and applying a BCR threshold of 1, indicates that pavement investment needs will be on the order of $27–$32 billion annually over the next 20 years, based on VMT growth ranging from 0.75 to 2.0 percent per year.

The above spending level represents a large increase over existing spending on Interstate pavements. As previously noted (see Figure 5-1), in 2014 states spent about $17 billion on Interstate pavement rehabilitation and reconstruction, representing nearly 67 percent of the $25 billion in total capital expenditures devoted to Interstates that year.[5]

Bridge Investment Needs

The components of bridges, as typically described, are (1) the substructure (abutments and columns), (2) the superstructure (girders, trusses), and (3) the deck. Each of these components has its own service life and repair and maintenance requirements that depend on design and materials (e.g., prestressed concrete or steel) and exposure to weather and traffic. Well-maintained substructures and superstructures, especially those not exposed to chlorides from deicing-chemical runoff and saltwater splash and spray in marine environments, can last well over 50 years—potentially more than 75 years in parts of southern and western states where these adverse conditions do not exist. Many concrete deck systems, by comparison, were designed to be serviceable for 30 to 50 years; however, their lives were often shortened by exposure to heavy truck traffic and, in colder regions, by frequent and heavy applications of road salt (Azizinamini et al. 2014, 27). Many early Interstate bridge decks exposed to chlorides existing in marine environments and deicing chemicals failed quickly as the chlorides reached

[5] This and subsequent references to Interstate capital spending by state departments of transportation (DOTs) in 2014 are from FHWA (2016b, Table SF-12A).

uncoated reinforcing steel within the deck, causing corrosion that induced concrete surface spalling and potholes.

Decks account for the majority of state spending on bridges, mainly for repair and rehabilitation necessitated by damage from the effects of corrosion and heavy traffic loadings (Azizinamini et al. 2014, 15, 27). In the case of bridge substructures, chloride contamination of joints, bearings, and piers (due to runoff of salt-laden melt from decks) has also been a major cause of the need for maintenance and rehabilitation work. Over the past 30 or more years, damaged Interstate bridge decks and substructures have been rebuilt using epoxy-coated and zinc-coated reinforcement and stainless steel, which have substantially limited corrosion damage caused by deicing treatments and saltwater exposure.

Bridge Investment Needs Estimated Using NBIAS

NBIAS, FHWA's bridge investment analysis tool, generates estimates of improvement needs for Interstate bridges that, like those generated by HERS (which does not contain bridge information), are based on benefit-cost calculations. The NBIAS model, which is discussed in more detail in Appendix H, uses bridge condition data recorded from state inspections as reported in the National Bridge Inventory database. For each bridge element (e.g., deck, railings, girders, floor beams), the model considers the state of deterioration and whether there is a deficiency, identifies candidate actions for addressing the deficiency (which can include maintenance, repair, rehabilitation, and strengthening), and computes the costs and benefits of taking those actions. If the improvements are not cost-beneficial, infeasible because of bridge design, or impracticable because of deteriorated structural condition, a bridge replacement "need" is generated based on state-reported structural condition values for new bridges.

To make calculations, NBIAS uses a set of unit costs for various improvement and preservation options; the model contains some 200 performance measures for assessing each option. The desired performance levels can be specified, as can constraints on spending and an acceptable BCR. Questions that NBIAS can address include, for example, what level of spending is required annually to maintain current bridge conditions over, say, the next 20 years and what user benefits might be achieved with a given set of improvement investments?

To estimate Interstate bridge investment needs for the next 20 years, the committee applied NBIAS differently from HERS because VMT growth rates in the range of 0.75 to 2.0 percent per year were found to have only a small impact on the results. Rather than calculating all improvements that would meet or exceed a specified BCR and tabulating the resulting spending levels, different annual bridge spending levels were specified to test how they would impact the physical condition of Interstate bridges.

TABLE 5-4 Estimated Annual Investments Needed to Improve Interstate Bridges Over the Next 20 Years

Average Annual Investment Level Over 20 Years (2016 dollars)	Percentage of Deck Area That Is Structurally Deficient		Health Index	
	Year 2016	Year 2036	Year 2016	Year 2036
$2.85B	11.6	13.5	92.8	90.1
$3.80B (current level)	11.6	7.6	92.8	93.0
$4.8B	11.6	3.5	92.8	94.9

NOTE: Analysis conducted using the National Bridge Investment Analysis System (NBIAS).

Two measures were used for bridge condition: (1) the percentage of total Interstate bridge deck surface area that would be rated as structurally deficient, and (2) a version of California's bridge "health" index, which is based on an evaluation of the condition of 10 to 12 important bridge elements (from the substructure, superstructure, and deck), which was applied to the Interstate bridge inventory as a whole. In a sense, the entire inventory of Interstate bridges was treated as one structure encompassing all element quantities and condition distributions within the inventory.[6]

Three annual spending levels—including the current level of $3.8 billion per year as reported in the 2015 *C&P* report (FHWA 2016a, Exhibit 7-18)—were used to determine impacts on bridge condition over the next 20 years. Table 5-4 presents the results of this analysis. They suggest that, unlike current pavement investments, current levels of Interstate bridge investment would lead to continued improvements in the structural conditions of bridge decks and in the overall health of the inventory. The percentage of structurally deficient deck area would be expected to decrease by several percentage points, and the overall health index of the system's bridges would remain essentially unchanged (increasing slightly from 92.8 to 93, where a high health index indicates better condition). Index values in the 90s suggest that bridges in the system are in generally good condition. A $1 billion increase in annual bridge spending would provide large additional reductions in the amount of deficient deck area but increase the health index only modestly.

Summary Assessment of Bridge Investment Needs

The NBIAS analysis suggests that states are already devoting sufficient funds to continuing to maintain and improve Interstate bridges, which

[6] For a complete description of this index, see FHWA (2016c).

tends to be a high priority for safety reasons and because of the high value and use of Interstate bridges. Somewhat higher annual investments (~25 percent) would lead to further improvements in physical condition by reducing structurally deficient deck area; however, this deficiency is generally not considered to be a safety concern but a serviceability or ride quality issue. An investment level of $4 billion per year to further improve the condition of deck surfaces—similar to what is being spent today—appears appropriate for bridge investment over the next 20 years.

ESTIMATING 20-YEAR CAPACITY INVESTMENT NEEDS

At a Glance

- Assuming an investment strategy that encompasses all cost-beneficial improvements, the annual 20-year investment for Interstate highway lane additions would be on the order of $13–$31 billion, depending on realized vehicle-miles traveled (VMT) growth. These investment needs estimates are made with much less confidence than estimates for pavement and bridge work because they are highly dependent on assumptions about future travel demand, which is difficult to predict.
- Interchanges are an important source of bottlenecks and traffic delays; however, improvements to interchanges are not included in the existing analytical models. Similarly, no national inventory of Interstate interchanges or records of their condition exist, making it difficult to develop even rough estimates of future renewal requirements.
- Adding physical capacity is not the only means of alleviating congestion; ramp metering, incident management systems, hard shoulder running, managed lanes, adaptive speed limits, integrated corridor management, and weather management all can serve as means of accommodating increasing traffic volume. These improvements are estimated to require a $2 billion average annual investment over the next 20 years.
- Toll-managed, truck-only, and reversible lanes cannot readily be examined using standard models; therefore, supplemental techniques were required for their evaluation herein. Of these three specifications, toll-managed lanes had the most effect in reducing congestion—by about one-third under most circumstances. Reversible lanes require the least investment but are often difficult to implement. Truck-only lanes would be easiest to implement but would incur relatively high costs to produce relatively smaller congestion-reducing effect relative to toll-managed lanes.

Along with these substantial investments in pavement and bridge rehabilitation and reconstruction, additional investments will be required to expand and manage the Interstate Highway System's capacity to handle future traffic. For reasons noted earlier, investments that will be required to accommodate this traffic demand are much more difficult to project because they are highly dependent on assumptions about future travel demand and its relationship to capacity. HERS can be a valuable tool for determining how different VMT growth rates affect system operating performance and capacity investment needs, but it has important limitations when considering investments over long periods when myriad factors can change to affect travel behavior and as travelers respond to changes in capacity. Accordingly, the estimates of capacity-related investment needs that follow are made with much less confidence than the estimates for pavement and bridge work, which are affected far less by changes in VMT. By using a range of historically informed VMT growth rates, the committee could, at best, make rough approximations of the magnitude of spending that might be needed for physical and operational capacity improvements over the next 20 years.

In the sections that follow, various capacity investments are assessed using HERS under alternative rates of VMT growth, starting with the option of adding more general-purpose lanes and making operational improvements (e.g., incident management). Consideration is then given to the use of toll-managed lanes, truck-only lanes, and reversible lanes. These latter options cannot readily be examined using HERS, and therefore required supplemental evaluation.

Adding General-Purpose Lanes

When VMT is assumed to grow, HERS considers a range of options for accommodating that growth in way that keeps congestion within defined parameters and calculates the BCRs for each option. Adding capacity by constructing a new lane is one option. Table 5-5 displays how adding lanes affects levels of Interstate traffic congestion using a BCR of 1 or higher. An annual expenditure of $22 billion over the next 20 years keeps congestion at levels comparable to those of today when a VMT growth rate of 1.5 percent per year is assumed. By comparison, a VMT growth rate of 2.0 percent per year requires expenditures of $31 billion annually over the next two decades, and even with that larger investment, congestion increases by nearly 25 percent over today's level. In this case, additional investments beyond $31 billion would not be cost-beneficial, mainly because of the difficultly of acquiring the needed right-of-way in urban areas.

The $22 billion per year that HERS estimates would be required for lane additions to keep delay at roughly today's levels (following a 20-year

TABLE 5-5 Annual 20-Year Investment Required for Interstate Highway Lane Additions to Accommodate Alternative Rates of Growth in Vehicle-Miles Traveled (VMT), Showing the Impact on Delay by the End of the 20-Year Period

	Annual VMT Growth Rate		
Investment Criteria	**0.75%**	**1.5%**	**2.0%**
BCR ≥1			
Annual Investment (billions)	$13.2	$21.8	$31.3
Annual Peak-Period Delay in Person-Hours (millions)	1,800	2,500	3,100
BCR ≥1.5			
Annual Investment (billions)	$11.7	$13.4	$19.3
Annual Peak-Period Delay in Person-Hours (millions)	2,910	3,230	4,250

NOTE: Based on analysis using the Highway Economic Requirements System (HERS).

period of 1.5 percent annual VMT growth) might be an acceptable investment. However, adding physical capacity is not the only means of alleviating congestion, especially when delays are caused by nonrecurrent events such as traffic indents (e.g., crashes, disabled vehicles), road construction, and special events. The potential for accompanying investments in operational means to prevent or alleviate congestion is therefore considered below.

It should be noted that the figures in Table 5-5 do not include investments to upgrade the Interstate Highway System's many interchanges. As previously noted, interchange improvements are not treated in HERS—a notable deficiency because interchanges are an important source of bottlenecks and traffic delay. Interchanges can be costly to reconfigure and reconstruct, creating operational challenges and consuming considerable right-of-way. While newer interchange designs that improve safety (e.g., "diverging diamonds") have lessened the required right-of-way, renewal and modernization of Interstate interchanges will remain costly undertakings. Case studies indicate costs ranging from $80 million to more than $600 million per interchange, depending on the complexity of the interchange and its context (see Appendix I). These projects can entail a wide range of activities, including reconfiguration, widening, structure replacement, realignment, and relocation. Inasmuch as these investments are not included in the HERS output, one could consider the investment levels in Table 5-5 to be lower bounds.

Adding Operational Improvements

Options for accommodating various traffic volumes that are amenable to analysis using HERS are ramp metering, incident management systems, hard shoulder running, managed lanes, variable speed limits, integrated corridor management, and weather management. Figure 5-6 shows how investing in a combination of these operational improvements affects delay under different conditions of annual VMT growth. It assumes that all the investments in pavement improvements and lane additions discussed above that have a BCR of 1 or higher are accompanied by operational improvements (a $2 billion per year investment). The additional investment in operational mechanisms, representing a substantial increase over current spending on operational systems, leads to a roughly 10 percent reduction in delay. The effect of this $2 billion per year investments on delay is noted later in this chapter when 20-year investment needs are summarized.

Using Toll-Managed, Truck-Only, and Reversible Lanes

As noted earlier, HERS cannot be used to consider the full range of options for renewing and modernizing the Interstate Highway System. Excluded strategies include toll-managed lanes, truck-only lanes, and reversible lanes. While specific conditions under which each of these three strategies would be effective may differ, all would have their greatest applicability to urban

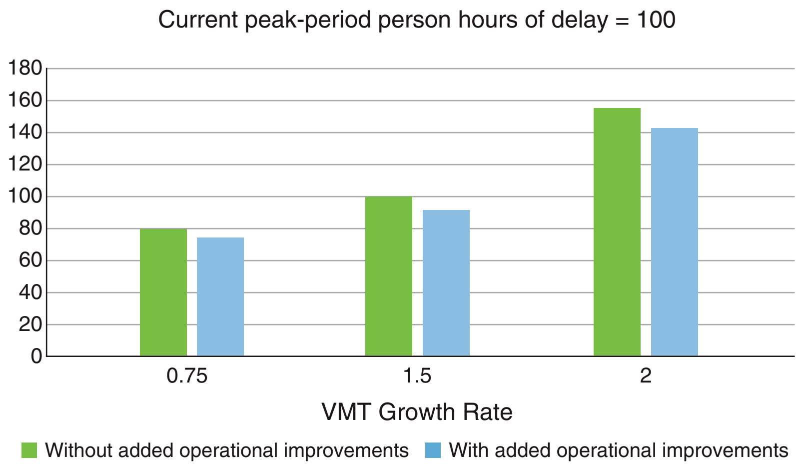

FIGURE 5-6 Effects on traffic delay at the end of the 20-year period after adding $2 billion per year in operational improvements (to pavement and capacity projects).
NOTE: Benefit-cost ratio (BCR) ≥1.

corridors that are the locations of much of the country's traffic growth and suffer chronically high peak-period congestion.

Tolling is increasingly being used to allocate scarce urban highway capacity and is typically implemented by adding toll-managed lanes, sometimes called express toll lanes. Toll charges usually vary depending on time of day and/or traffic flow conditions and as such are a form of congestion pricing. State spending on toll-managed lanes is not reported separately to FHWA, but a survey found 41 deployments around the country, including 26 on Interstate highways.[7] Reversible lanes are usually implemented as part of a larger corridor management strategy, and often involve the deployment of movable barriers on existing lanes to increase capacity in the direction of the heaviest traffic flow. Unlike toll-managed and reversible lanes, dedicated truck lanes do not exist on the Interstate Highway System. A number of proposals have been made for the deployment of tolled, dedicated truck lanes on Interstate corridors that have heavy freight volumes (e.g., the I-710 Freeway Separated Truck Lanes Proposal, Georgia I-75 Separated Truck Lane Proposal, and I-70 Corridor Dedicated Truck Lane Study). Some of these proposals envision restrictions on lane use to achieve benefits other than volume control, such as encouraging use of low- or zero-emission trucks.

To estimate the effects of these three strategies in reducing congestion under the three alternative VMT growth rates considered herein, candidate Interstate segments were identified from HPMS data under the assumptions and rules detailed below.

Toll-Managed Lanes

An FHWA compilation of managed-lane projects indicates that adding a toll-managed lane costs about $4 million per mile and can be expected to enable a free-flowing capacity of 1,600 vehicles per hour per lane (vphpl) (FHWA n.d.-f). Using the highway segments in HPMS and assuming that a toll-managed lane would be deployed only in circumstances in which removing 1,600 vphpl from the general-purpose lanes and assigning that traffic to the toll-managed lane would still result in predicted congestion on the general-purpose lanes. The analysis reported herein assumes that congestion occurs when the ratio of peak volume to capacity on a lane is greater than or equal to 0.95. This rule is necessary because congestion must remain on the general-purpose lanes to continue to entice drivers to pay for the premium service. Thus, some sections that have volume-to-capacity ratios somewhat higher than 1.0 do not get a managed lane because not enough

[7] See https://managedlanes.files.wordpress.com/2017/07/0-ml-database-green-yellow-blue-key-march-2017.pdf.

congestion remains in the general-purpose lanes after the premium lane has been added.

Truck-Only Lanes

Data from a recent NCHRP report indicate that adding a truck-only lane costs about $6.7 million per mile (Cambridge Systematics, Inc. 2010). The analysis reported herein using the highway segments in HPMS further assumes that truck lanes are deployed if the following condition is met: predicted truck volumes for the highway must exceed 10,000 vehicles per day, or the predicted percentage of trucks on the segment must exceed 25 percent when the volume-to-capacity ratio for the segment is between 0.9 and 1.4. Moreover, the new truck lane must have the potential to reduce the volume-to-capacity ratio (in the general-purpose lanes) to 0.9 or less (i.e., the new lane would reduce congestion meaningfully). Although not investigated in this analysis, the advent of autonomous and connected vehicle technologies could result in truck lanes with platooning, thereby increasing capacity potential. How these vehicle technologies will develop and be deployed would clearly influence this alternative.

Reversible Lanes

Available information suggests that the cost per lane-mile of deploying a reversible lane is $1.7 million (Mobility Investment Priorities n.d.). In assessing this option (again using the highway segments in HPMS), it is assumed that a reversible lane will be deployed if no congestion occurs in the direction opposite to the direction of traffic on the reversable lane and that predicted speeds in the treated direction are increased to at least 45 mph.

Results

Table 5-6 presents the results of the analyses of these three congestion-reduction treatments. Of the three options, toll-managed lanes have the greatest impact, reducing congestion by about one-third on the corridors where they are deployed. Their overall effect is limited, however, by the fact that most congestion occurs in metropolitan areas, where right-of-way constraints and community concerns make the addition of new lanes cost-prohibitive. Although reversible lanes require the least investment, they have the least applicability and thus a limited effect on total traffic congestion. Truck-only lanes have the greatest applicability but relatively high costs, and produce less congestion reduction than toll-managed lanes.

Because these three congestion-reduction treatments are generally substitutes for one another and for some of the improvements addressed earlier,

TABLE 5-6 Congestion Impact and Cost of Alternative Highway Operations Treatments

	0.75% Annual VMT Growth		
	29,057		
Deficient 2036 Interstate Lane-Miles Before Treatment*	**Miles Added**	**Reduced Congestion**	**20-Year Cost**
Truck-Only Lanes	7,000	16%	$46.9B
Toll-Managed Lanes	4,488	29%	$18B
Reversible Lanes	393	4%	<$1B

	1.5% Annual VMT Growth		
	49,155		
Deficient 2036 Interstate Lane-Miles Before Treatment*	**Miles Added**	**Reduced Congestion**	**20-Year Cost**
Truck-Only Lanes	9,479	15%	$63.5B
Toll-Managed Lanes	8,775	32%	$39B
Reversible Lanes	418	3%	<$1B

	2.0% Annual VMT Growth		
	66,549		
Deficient 2036 Interstate Lane-Miles Before Treatment*	**Miles Added**	**Reduced Congestion**	**20-Year Cost**
Truck-Only Lanes	11,481	12%	$78B
Toll-Managed Lanes	15,899	34%	$64B
Reversible Lanes	382	2%	<$1B

*Predicted volume-to-capacity ratio >1.

the cost estimates in Table 5-7 cannot be added to the numbers in the summary table in the following section.

SUMMARY OF 20-YEAR INVESTMENT NEEDS

Assuming Interstate traffic growth rates derived from forecasts of U.S. population and economic growth, FHWA's HERS and NBIAS models indicate that a major additional commitment of resources will be needed to renew and modernize the Interstate Highway System over the next 20 years. These resources will be required in part to offset deferred investments that have the left portions of the system's foundation in a state of disrepair and in part to accommodate the system's continued aging and projected growing traffic demands.

TABLE 5-7 Estimated Spending Needs for Interstate Highway Renewal and Modernization Over the Next 20 Years (minimum benefit-cost ratio [BCR] = 1.0)

		Average Annual Investment ($ billions)		
	2014 State and Federal Investment[a,b] ($ billions)	Annual Growth in Vehicle-Miles Traveled (VMT)		
		Modest	Nominal	High
		0.75%	1.5%	2%
Resurfacing, partial and full reconstruction	$16	$27	$29	$32
Bridge rehabilitation and replacement	$4	$4	$4	$4
Rehabilitation and Reconstruction Subtotal	$20	$31	$33	$36
Capacity additions	$1	$13	$22	$31
Operations	$0.4	$2	$2	$2
Capacity-Related Subtotal	$1.4	$15	$24	$33
Condition and Performance After 20 Years If All Investments Are Made	$21.4	$46	$57	$69
% miles with poor pavement surface	2%	4%	4%	4%
Average annual peak-period delay (billions of person-hours)	2.4	1.8	2.5	3.1
Annual hours of peak-period delay per person[c]	11	9	12	15

[a] Data from FHWA (2016b, Table SF-12A).
[b] Investments in 2014 also included $2.2 billion in new Interstate construction not included in this total.
[c] The figures for person-hours of delay from the Highway Economic Requirements System (HERS) analysis are for the weekday peak periods in urbanized areas. To estimate the hours of delay per person, the total population in urban areas (220,482,000 as used in HERS) was adopted.

Table 5-7 summarizes estimates derived from the models used herein, in some cases supplemented by additional sources of information. The table includes only improvements that confer positive net benefits (BCR ≥1). Depending on the rate of VMT growth realized—from 0.75 to 2.0 percent per year—the projected investment required for a 20-year Interstate renewal and modernization program is on the order of \$45–\$70 billion annually, with the "nominal" investment being \$57 billion annually (VMT growth = 1.5 percent per year). While the bulk of this investment would be devoted to reconstructing the system's pavement structures, substantial resources are also needed to enhance and align the system's capacity, especially if VMT growth is at the higher end of the range. In the latter instance, investments in enhancements in addition to widening will almost certainly be required, including operational investments that better allocate capacity, such as through congestion pricing of lanes in urban areas where land is both scarce and expensive.

Expenditures of the magnitude displayed in Table 5-7 represent major increases over current Interstate investments of about \$20–\$25 billion annually. If the nominal VMT growth rate of 1.5 percent per year is assumed, investments over the coming 20 years will need to average \$57 billion annually—more than double the spending level of today.

Even with these large expenditures, it is notable that some aspects of Interstate condition and performance would not improve, and perhaps deteriorate, relative to current conditions after 20 years. For example, if VMT grows 1.5 percent per year, even an average annual expenditure of \$57 billion for pavement, bridge, and capacity-related improvements would result in levels of traffic delay comparable to today. To achieve much lower levels of delay (e.g., 75 percent of current peak-period hours of delay), as shown in Figure 5-7, would also require much higher levels of spending. Those much higher spending levels would not be justified on a benefit-cost basis, as calculated by the models.

Figure 5-8 shows how increasingly higher investment totals would affect pavement surface condition and traffic delay depending on assumed rates of growth in VMT. In the case of nominal VMT growth (1.5 percent per year), average annual investments would need to be three times higher than they are today (>\$75 million per year) to keep pavement surface conditions comparable to existing conditions but to reduce delay by 25 percent from current levels. These expenditure requirements would need to increase by another large increment if VMT is assumed to grow at annual rate of 2 percent. Annual spending would need to be double existing levels even if VMT is assumed to grow at the more modest pace of 0.75 percent annually. Again, these much higher spending levels are not economically justified according to the models.

All of these projections are, of course, based on models that have shortcomings acknowledged herein. It is the committee's judgment, however,

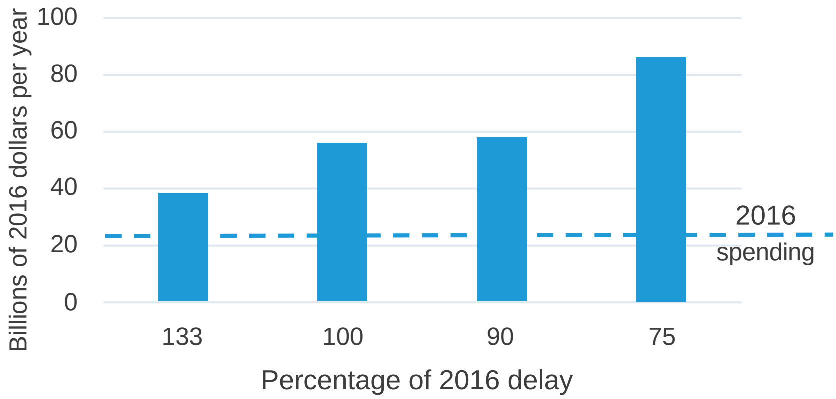

FIGURE 5-7 Average investment (federal and state) per year to achieve specified peak-period delay levels in 20 years relative to 2016 (assuming 1.5 percent annual growth in vehicle-miles traveled [VMT]).

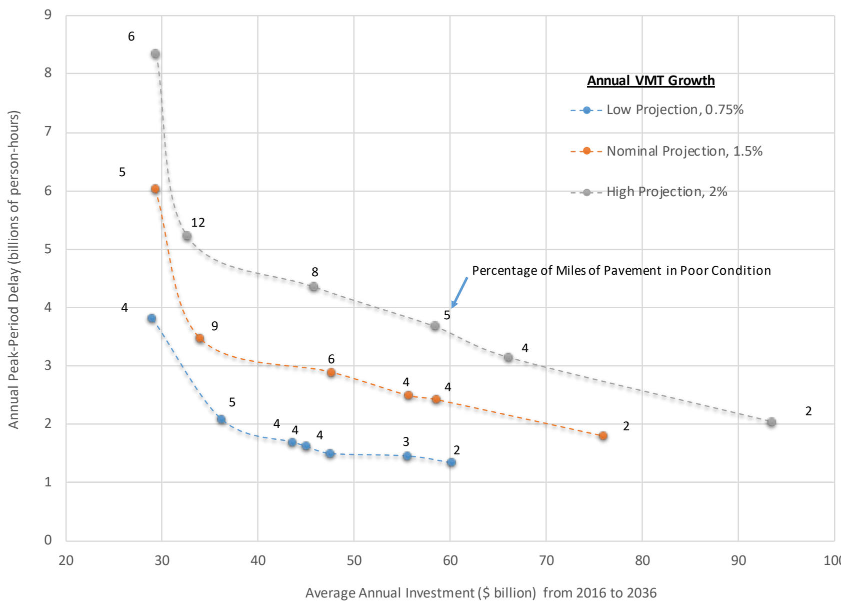

FIGURE 5-8 Modeled impact of annual Interstate investments on delay and pavement surface condition after 20 years assuming different rates of annual VMT growth.
NOTE: Investments are in constant 2016 dollars.

that the predicted totals are more likely to underestimate than overestimate actual investment needs. This judgment is based on the fact that, irrespective of the specific rates of growth in traffic over the next two decades, the existing system has a large backlog of work that will require substantial investment in itself. Although proven durable, the Interstate System's roadway foundation will eventually become unserviceable, and much of it is already more than 50 years old.

It must also be recognized that the nation's population is increasing, further concentrating in large metropolitan areas where the most congested highways exist. The need to invest in both the foundation and the traffic capacity of the Interstate System will fall disproportionately on urban portions of the system, where construction and reconstruction costs are the highest, and perhaps underestimated by the models.

SUPPLEMENTAL INVESTMENTS IN RESILIENCE AND RIGHTSIZING

The above estimates do not include consideration of three important needs, discussed in Chapters 3 and 4, that are likely to have a profound impact on the Interstate Highway System, particularly beyond the 20-year period that is the focus of this chapter. The first is to make the system more resilient to the effects of climate change. The second is to rightsize the system's footprint in response to a geographically shifting population and economy, including community concerns about the intrusiveness of some Interstate highways. And the third is to adapt to rapidly advancing technologies, including an all-electric vehicle fleet, fully automated vehicles, and the expanding use of drones.

Although federal-aid funds for planning and research can be used by states and metropolitan areas to conduct vulnerability assessments and analyze adaptation options, there is no special federal funding program for resilience (FHWA n.d.-b). FHWA has reported that more than $350 million was expended on highways in the Northeast that were damaged during Hurricane Sandy in 2013 (FHWA n.d.-e). Nonetheless, the investments for highway repairs are only a portion of the costs resulting from the Interstate System's lack of resilience: extreme weather events also incur significant economic costs due to highway closures and their impact on commerce. Should the effects of climate change become even more prominent and problematic over the next two decades, additional expenditures will be needed to make the Interstates more resilient. Importantly, there may be many cost-effective steps that could be taken in the years just ahead to improve Interstate resilience, particularly considering the long expected lifetimes of highway assets.

With regard to rightsizing, FHWA has established criteria for additions and withdrawals of Interstate Highway System routes (see Box 5-4).

BOX 5-4
Federal Criteria for Interstate Route Additions and Withdrawals

In addition to the Interstate routes originally authorized, until 1978 Congress approved the addition of new corridor-miles and expanded eligibility for Interstates Construction (IC) funds. The Surface Transportation Assistance Act of 1978, however, prohibited the use of IC funds for any new miles designated after passage of the act. A total of 42,795 miles had been designated for development with IC funds before this measure was enacted. Under current law, FHWA, at the request of a state or states, can designate sections of the National Highway System as new segments of the Interstate Highway System, although doing so does not authorize additional funding. The guidance criteria for evaluating requests for new Interstate routes are as follows (CFR Title 23 § 470.111—*Interstate System Procedures. Appendix A*).

1. The proposed route should be of sufficient length to serve long-distance Interstate travel, such as connecting routes between principal metropolitan cities or industrial centers important to national defense and economic development.
2. The proposed route should not duplicate other Interstate routes. It should serve Interstate traffic movement not provided by another Interstate route.
3. The proposed route should directly serve major highway traffic generators. The term "major highway traffic generator" means either an urbanized area with a population of more than 100,000 or a similar major concentrated land use activity that produces and attracts long-distance Interstate and statewide travel of persons and goods. Typical examples of similar major concentrated land use activities would include a principal industrial complex, government center, military installation, or transportation terminal.
4. The proposed route should connect to the Interstate System at each end, with the exception of Interstate routes that connect with continental routes at an international border, or terminate in a "major highway traffic generator" that is not served by another Interstate route. In the latter case, the

While these criteria are intended to ensure connectivity and prevent duplication, they distinguish among investments that would serve the national interests, as opposed to serving mainly state or local interests. The criteria include grounds for replacement of Interstate highway segments (FHWA n.d.-c), including replacement of what some view as "overbuilt" urban Interstate spurs that terminate in downtown areas but might better serve community interests if downgraded to allow for more local-use access, or even removed. As of 2016, FHWA had received inquiries from 12 states on how to withdraw Interstate segments (involving 17 Interstate segments). The agency has approved three such requests in recent years (FHWA n.d.-g). In 2008, for example, the District DOT (DDOT), in Washington, DC, requested the withdrawal of a segment of I-295 that was part of a longer terminus of the Interstate route should connect to routes of the National Highway System that will adequately handle the traffic. The proposed route also must be functionally classified as a principal arterial and be a part of the National Highway System.

5. The proposed route must meet all the current geometric and safety standards criteria as set forth in 23 CFR part 625 for highways on the Interstate System, or a formal agreement to construct the route to such standards within 25 years must be executed between the State(s) and the Federal Highway Administration. Any proposed exceptions to the standards shall be approved at the time of designation.
6. A route being proposed for designation under 23 U.S.C. 103(c)(4)(B) must have an approved final environmental document (including, if required, a 49 U.S.C. 303(c) [Section 4(f)] approval) covering the route, and project action must be ready to proceed with design at the time of designation. Routes constructed to Interstate standards are not necessarily logical additions to the Interstate System unless they clearly meet all of the above criteria.

Withdrawal or removal of Interstate highways is also allowed (FHWA n.d.-c). Reasons identified in the criteria for withdrawal include urban Interstate spurs that terminate in downtown areas and might better satisfy local transportation and livability needs if they were downgraded to urban routes. Only the transportation agency in the state in which the highway is located can request the withdrawal of Interstate sections/corridors, and such withdrawals must be formally requested to FHWA. Title 23 of the Code of Federal Regulations also regulates the use and disposition of property previously acquired by states for Interstate segments. It addresses the process by which and extent to which a payback to the federal government is required for property acquired by states with the participation of federal-aid highway funds (23 CFR 480*).

*Code of Federal Regulations, Title 23, Part 480, https://www.gpo.gov/fdsys/pkg/CFR-1998-title23-vol1/xml/CFR-1998-title23-vol1-part480.xml.

route that was never completed. In its place, DDOT planned to convert the withdrawn Interstate segment to an urban boulevard.

Primary candidates for upgrades to the Interstate System are highways in the National Highway System (NHS) that are currently functioning in a manner similar to the Interstates and that can be expected to experience heavy demand over the next 20 years. To estimate how much mileage would qualify, it is assumed that VMT grows at the nominal projected rate (1.5 percent per year) over all NHS routes and that 2016 HPMS data can be used to estimate the impacts on traffic volumes. When traffic reaches a volume-to-capacity ratio greater than or equal to 0.9 and an annual average daily traffic (AADT) of 30,000 or more on a given highway segment, it is assumed that an investment of $10 million per mile (based on experience with I-69 as discussed in Chapter 3) would be required to convert the highway to an Interstate. About 150 rural NHS miles and more than 3,200 urban NHS miles would qualify under these criteria, as shown in Table 5-9. This added mileage would require an investment of about $32 billion. (Obviously, some of these miles would not be candidates for conversion to Interstates because they involve only short segments as opposed to full routes.)

SUMMARY

The committee used standard FHWA models for estimating highway and bridge investment needs as the primary basis for estimating investment levels required to renew and modernize the Interstate Highway System over the next 20 years, considering a range of rates of traffic growth. Whether a potential investment is viewed as justified ultimately depends on the highway condition and performance outcomes considered acceptable. While such outcomes are largely subjective, the estimates developed in this

TABLE 5-9 Candidate NHS Mileage for Upgrade to Interstate Status by State Based Only on Predicted Levels of Congestion with an Annual VMT Growth Rate of 1.5 Percent per Year

	Center-Line Mileage			Center-Line Mileage	
	Rural	**Urban**		**Rural**	**Urban**
Alabama		8.8	Missouri		21.2
Arizona		66.1	Nebraska		6.6
Arkansas		14.8	Nevada		27.0
California	64.2	746.1	New Hampshire	1.4	33.2
Colorado	1.7	55.3	New Jersey	5.9	166.9
Connecticut	0.7	100.6	New York		224.2
Delaware	11.0	13.6	North Carolina		52.8
District of Columbia		1.6	Ohio		58.7
Florida	13.1	263.6	Oklahoma		39.4
Georgia		44.9	Oregon		33.2
Hawaii		0.6	Pennsylvania	5.6	72.6
Illinois		15.9	Rhode Island		7.6
Indiana		0.3	South Carolina		0.5
Kansas		23.0	Tennessee		47.2
Kentucky		11.4	Texas		496.8
Louisiana		1.6	Utah	0.6	6.3
Maryland		110.6	Virginia	8.7	61.5
Massachusetts	2.1	84.6	Washington	1.4	44.8
Michigan	33.9	130.0	Wisconsin		35.9
Minnesota		104.4			
Mississippi		0.9	**All States**	**150.3**	**3,235.1**

chapter were derived from modeled benefit-cost calculations—the approach recommended by Congress in requesting this study. The following estimates are intended to provide general guidance regarding the magnitude of investments required over the next 20 years under a moderate investment strategy that encompasses all cost-beneficial improvements.

Total investment needs. Using the methods described in this chapter, the committee derived a nominal estimate of $57 billion total average annual expenditures (with a range of $45–$70 billion, depending on the choices to be made and uncertainties).

Pavement investment needs. Investment in pavements is estimated to be on the order of $27–$32 billion annually over the next 20 years, based on assumed rates of growth in VMT ranging from 0.75 to 2.0 percent per year. This figure includes the cost of fully reconstructing Interstate pavements and their foundations.

Bridge investment needs. Modeling suggests that states are currently devoting sufficient funds to maintaining and improving Interstate bridges. Somewhat higher annual investments (~25 percent) would lead to further improvements in physical condition by reducing deficient deck area; however, this deficiency is generally considered a serviceability or ride quality issue, not a safety concern. An investment level of $4 billion per year—similar to what is being spent today—is a reasonable representation of the Interstate System's bridge investment needs for the next 20 years.

Investment in lane additions. Under the assumed moderate investment strategy, the annual 20-year investment required for Interstate highway lane additions is nominally $22 billion, with a potential range of $13–$31 billion, depending on the rate of traffic growth. These investments would result in annual peak-period delays of approximately 1,800–3,100 million person-hours per year, also depending on the rate of traffic growth.

Investment in interchanges. Interchanges are an important source of bottlenecks and traffic delay; improvements to interchanges, however, cannot be modeled using current capabilities. No national inventory of Interstate interchanges or records of their condition exist, thus making it difficult to develop even rough estimates of future renewal requirements.

Investment in operational measures. Deploying means other than physical additions to the Interstate System, such as ramp metering, incident management, hard shoulder running, managed lanes, variable speed limits, integrated corridor management, and weather adaption, is estimated to require a $2 billion average annual investment.

Supplemental investments. Finally, it is important to note that the nominal estimate of $57 billion total average annual expenditures (with a range of $45–$70 billion, depending on the choices to be made and uncertainties) is incomplete because it does not include the investments required in several areas that cannot be responsibly estimated at this point but are certain to require billions, perhaps many billions, in additional spending. These investments would be necessary to reconfigure and reconstruct many of the system's roughly 15,000 interchanges (Gehr 2010, 9), make the system more resilient to the effects of climate change, expand and allocate more efficiently system capacity in and around metropolitan areas, and begin to adapt to major technological changes affecting both vehicles and highways.

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Abbreviations

FHWA	Federal Highway Administration
TRB	Transportation Research Board

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6

Investment Funding Options

Chapter 5 provides estimates of the annual investment needed to renew and modernize the Interstate Highway System over the next 20 years under a nominal and two excursions of traffic growth rates. As discussed in that chapter, if investments are made in all improvements that are cost-beneficial, spending in the nominal case will be $57 billion annually, with higher and lower derivative cases of $45 billion and $70 billion, respectively, or in the range of 2 to 3 times current spending. The nominal figure assumes vehicle-miles traveled (VMT) will increase at approximately 1.5 percent per year. The lower figure assumes that VMT will grow at 0.75 percent per year, about the same pace as population growth. The higher figure assumes VMT will grow at 2 percent per year, which is more in line with historical growth. The present chapter considers how such spending levels might be accommodated.[1]

Funding for the federal-aid highway program has traditionally been based on a pay-as-you-go system,[2] with revenues obtained from users being dedicated to the federal Highway Trust Fund (HTF). Federal motor fuel taxes have traditionally accounted for most of the revenues to the HTF and have long been levied as a fixed amount per gallon—18.4 cents per gallon of gasoline and 24.4 cents per gallon of diesel fuel since last increased in

[1] The chapter does not consider specific financing instruments, such as bonds, but rather the taxes and other user fees that can generate the underlying revenues needed to pay for highway investments.

[2] The pay-as-you-go approach means that construction would proceed only at the same pace as revenues were received.

1993. However, HTF receipts have been stagnant, failing to keep pace with inflation and growth in motor vehicle travel in recent years (see Figure 6-1). Part of the reason for this circumstance is that the gasoline tax has not been increased in a quarter of a century—that is, since 1993. From the time the HTF was created in 1956 until 1993, Congress increased the fuel tax eight times, or about once every 4 to 5 years over a 37-year period, to offset the effects of inflation and support the demand for funds. Since 1993, however, the fuel tax rate has not changed, even as the price of motor fuel has increased considerably. In 1993, the federal tax accounted for about 17 percent of the average retail price of a gallon of gasoline, whereas in 2017 it accounted for only 8 percent (Statista 2018). The purchasing power of the 18.4 cent federal gasoline tax has eroded by more than 35 percent since 2003 (see Figure 6-2).

Another contributor to stagnation in HTF revenue is that the motor vehicle fleet has become increasingly more fuel-efficient, meaning that motorists are paying less in taxes per mile traveled even as they travel more and place more demands on the system. Since 1993, VMT fleetwide average fuel economy has increased by more than 7 percent (FHWA 1993, Table VM-1; 2017b, Table VM-1). To meet the growing demand for funding the federal-aid highway system's maintenance and operations, Congress has increasingly turned to general revenues to supplement the user taxes and fees flowing into the HTF. By 2020, Congress will have transferred $143.6 billion from general revenues to the HTF (Kirk and Mallett 2018).[3]

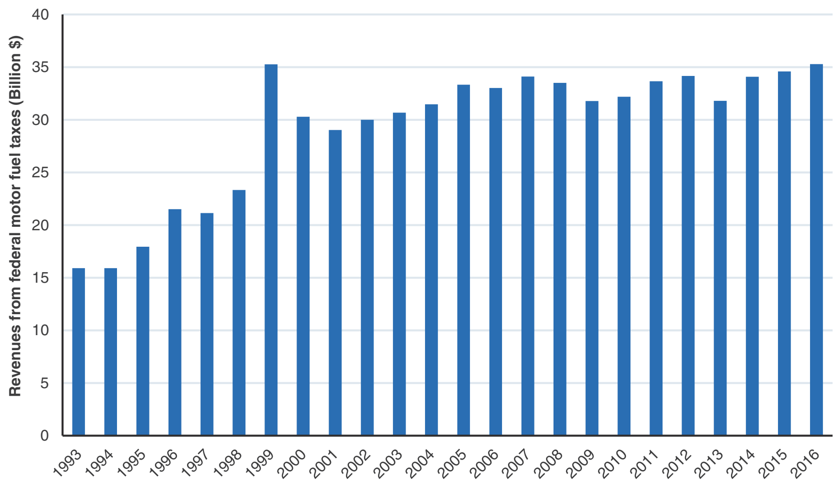

FIGURE 6-1 HTF revenues from federal fuel taxes, 1993–2016.
SOURCE: FHWA 2017a, Table FE-210.

[3] There have been more recent transfers of fuel tax receipts originally intended for deficit reduction to the HTF such that all federal gasoline and diesel taxes are now available for highway and transit programs.

FIGURE 6-2 Federal motor fuel tax revenues adjusted to 2003 dollars using the National Highway Construction Costs Index (NHCCI), 2003–2016.

Concerned about a pending shortfall in fuel tax revenues to the HTF, Congress established two separate commissions in 2005 to examine future surface transportation funding needs and recommend options for funding the system in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). These commissions considered many different means of addressing the funding gap but settled on a relatively small number as being suitable. The recommendations of these commissions, as well as other funding options, are discussed and evaluated in this chapter and in Appendix J.

The chapter begins with some historical background and briefly reviews the recommendations of the two commissions. It then presents criteria developed by the present committee to evaluate funding options. Next, candidate funding options—those based on user fees as well as some additional options—are described. For each option, pros and cons and institutional and policy considerations are presented. This review sheds light on opportunities and challenges presented by the different funding options. While these options could be applied individually or in combination—with the latter approach being more likely—each is considered separately to highlight its effects. The chapter closes with a summary of the more plausible choices for funding the renewal and modernization of the Interstate Highway System.

BACKGROUND

Beginning in 1916, the federal government began sharing in the cost of investing in new highways with the states on a 50/50 basis. In 1956, as described above and in Chapter 2, Congress established the HTF to pay for the federal government's new commitment to build an Interstate Highway System in partnership with the states. The federal share for new construction was set at 90 percent federal, 10 percent state, and new projects were funded on a pay-as-you-go basis with funds derived from fuel and other user fees (excise taxes) paid into the HTF. (In a few states, existing tolled highway facilities were grandfathered into the system; otherwise, tolling was prohibited on general-purpose lanes receiving federal aid.) As the primary source of revenue to the HTF, a new federal tax on motor fuels was set at 3 cents per gallon, an amount that was increased to 4 cents in 1959. At that time, the average price of gasoline at the pump was 31 cents per gallon (DOE 2016).

The original vision of Congress was that the HTF would exist only temporarily until the Interstate program was completed. Over time, however, the HTF grew to cover a variety of programs beyond the Interstates, such that the Interstate Highway System currently receives only about 30 percent of total federal aid to states for highways.[4]

Today, the HTF funds highway capital and maintenance; federal environmental, safety, and planning programs; and 2.85 cents of the federal gasoline tax is set aside for the Mass Transit Account (Kirk and Mallet 2018, 7–8). Thus, options to fund the Interstate Highway System depend on the manner in which Congress chooses to allocate funds for surface transportation programs overall. Over the course of previous authorizations for surface transportation spending, Congress has provided the states with more discretion over how federal aid is invested. The current authorization, for example, has no specific set-aside for the Interstates. Interstate spending, does, however, retain its favorable federal funding ratio for individual projects (90 percent federal), compared with other categories of federal aid for highways (80 percent federal).

[4] Federal highway legislation offers states considerable flexibility on how they spend federal aid (it is not allocated by highway class). In fiscal year 2014, state obligation of federal aid to the Interstate Highway System totaled about $11.2 billion (31 percent) of about $35.4 billion of federal highway aid provided to the states (see FHWA 2016a, Table FA-4C). Because about 15.5 percent of the federal gas tax is dedicated to transit, the share of total federal fuel taxes allocated to Interstates would be less than one-third of total federal aid for surface transportation derived from fuel taxes.

NATIONAL COMMISSION RECOMMENDATIONS

At a Glance

- Under the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, Congress created two commissions that made recommendations for funding federal-aid highways.
- Both commissions focused their recommendations on fuel taxes and other user fees, including raising and adjusting of taxes for inflation, evaluation of mileage-based user fees, and updating of truck-related fuel and excise taxes.

In 2005, Congress created the National Surface Transportation Policy and Revenue Study Commission (Policy Commission) within SAFETEA-LU with a mandate to consider funding options for all surface modes, but the Policy Commission also made recommendations specifically for funding federal-aid highways (National Surface Transportation Policy and Revenue Study Commission 2007). Congress also created the National Surface Transportation Infrastructure Financing Commission (Finance Commission) in SAFETEA-LU, with a mandate to consider funding options for both highways and transit (National Surface Transportation Infrastructure Financing Commission 2009). The Finance Commission evaluated roughly 30 different federal tax and user fee options against 14 different criteria. A summary of the Finance Commission's evaluation of revenue options appears in Appendix J, which includes an exhibit illustrating the revenue potential of the options considered.

Both SAFETEA-LU commissions focused their recommendations on user fees—for obvious reasons. The fuel tax and tolling are examples of user fees, and seek to relate the use of highways to payment for that use. They have the advantages of being generally equitable as well as relating user demand to the generation of revenues needed to supply that demand, in this case with highway capacity. Additionally:

- In recognition that federal fuels taxes, as applied, have been flat taxes whose value has been eroded by inflation, both commissions recommended adjusting the taxes in some fashion to account for inflation.
- Because fuel taxes also become less reliable as a revenue source as motor vehicle fuel economy improves and as more vehicles use electricity or alternative fuels, both commissions recommended

evaluating mileage-based user fees (MBUFs) to augment or replace fuel taxes.

- Both commissions recommended updating truck-related fuel and excise taxes to ensure that trucks pay user fees commensurate with the disproportionate pavement and bridge damage they produce.
- Recognizing that most Interstate congestion occurs on urban Interstates, where options to physically expand capacity are limited, both commissions recommended allowing states and metropolitan areas to toll new Interstate lanes and charge congestion tolls on existing lanes. The tolls would thus raise funds to support the addition of new capacity and provide a pricing mechanism to manage highway demand and supply more efficiently. Concerned that tolls on Interstates could be set in a manner that discriminates against out-of-state traffic and through traffic, both commissions recommended federal policies and procedures to guard against such practices.

EVALUATION CRITERIA

The committee developed the following criteria against which the various funding options reviewed in this chapter can be evaluated:

- Revenue potential—includes the ability to raise the large sums required for highway capital and maintenance and to sustain that revenue stream.
- Administrative burden—refers to the expense of collecting taxes and enforcing compliance.
- Efficiency impacts—considers whether the option encourages efficient use of the Interstate System and generates revenues that can cover investments in the system.
- Equity issues—cover a range of potential interest for policy makers, including disproportionate fee expenses in comparison with income, geographic fairness in how funds are raised and allocated, and allocation of fees or taxes in proportion to costs imposed by any party.
- Public acceptance potential—can be difficult to gauge, but may be indicated by such means as opinion polls and experience from prior applications.

USER FEE–BASED OPTIONS

At a Glance

The committee evaluated the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users commissions' recommendations for user fee–based solutions. The recommended options include

- Increasing motor fuel taxes and other existing federal user fees;
- Allowing states and metro areas to toll existing general-purpose Interstate highways; and
- Instituting mileage-based user fees for Interstate use to replace other user fees.

In the present committee's view, the two commission reports made a strong case for user fee–based solutions to fund the federal-aid highway program. Such solutions could also raise the revenue needed to fund Interstate Highway System renewal and modernization. These options could take the form of (1) traditional user fees (motor fuel taxes and excise taxes that apply to trucks) or other types of fees that involve direct charging for system use, namely (2) tolls, and (3) MBUFs.

Option 1: Increasing Motor Fuel Taxes and Other Existing Federal User Fees

Motor Fuel Taxes

Fuel taxation has proved invaluable over six decades by providing a source of revenue that is tied to use of the highway system, but its revenue-raising value has become imperiled by a reluctance over the past three decades, at least at the federal level, to raising taxes of any kind and especially fuel taxes. Nevertheless, one option for Congress to consider is a fuel tax increase sufficient to support the additional funding needed to renew and modernize the Interstate Highway System over the next two decades.

If the goal is to raise approximately $20 billion in new revenue to augment current annual spending on the Interstate System (increasing spending from $25 billion to $45 billion per year), an approximation developed in Appendix J indicate that the federal gasoline tax would need to be increased from 18.4 cents per gallon to nearly 30 cents per gallon within

10 years, assuming that VMT grows 1.5 percent per year (making certain other assumptions regarding changes in fleetwide average fuel economy and form of energy used by vehicles in the fleet). Diesel fuel tax rates for trucks would have to increase from 24.3 cents per gallon to approximately 40 cents per gallon. These rate increases would be roughly 60 percent over existing rates.

Pros: The fuel tax is a proven funding mechanism for generating revenue—particularly if adjusted periodically to account for inflation and improving fleetwide fuel economy. Motor fuels taxes continue to have majority public support as long as the funds derived are dedicated to the highway system (Agrawal and Nixon 2018).[5] Moreover, the motor carrier industry voiced support in early 2018 for a 20-cent per gallon increase (a near doubling) in motor fuels taxes to help fund improvements to the highway system (ATA 2018), as did the U.S. Chamber of Commerce (2018). The American Automobile Association (AAA) has also endorsed a fuel tax increase to pay for highways (AAA Newsroom 2015). Since 1993, when federal motor fuel taxes were last increased, three-quarters of the states have raised their fuel taxes (see Figure 6-3) (ITEP 2017). Twenty-six states raised fuel taxes in just the 4 years before mid-2017 (Quinton 2017).

A major advantage of the fuel tax is its very low administrative cost for collecting revenue—most estimates indicate collection costs are less than 1 percent of total revenues. Fuel taxes generally encourage efficient behavior insofar as the taxes paid are generally proportional to system use, but they may not be as efficient as a toll that relates the fee to a specific route used, or a congestion fee that relates the amount paid based on demand for a given facility at a specific time. Motor fuels taxes can be viewed as being equitable in the sense that users of gasoline- and diesel-fueled vehicles generally pay in proportion to their use of the overall highway system—although owners of vehicles that are more or less fuel-efficient will be impacted differentially. Equity with respect to income is discussed in the "con" section below.

Cons: Congress has been reluctant to raise federal fuel taxes. Moreover, federal fuel tax increases have in the past always been fixed dollar amounts (i.e., cents per gallon), which were eroded by inflation over time, although this shortcoming could be corrected if the rates were indexed, as recommended by the national commissions described above. (A percentage rate tied to the price of fuel is another option, but experience with this

[5] The survey results show that a majority of Americans would support higher taxes for transportation—under certain conditions. For example, 78 percent of respondents supported a gas tax increase of 10 cents per gallon to improve road maintenance, whereas support dropped to just 36 percent if the revenues were to be used more generally to maintain and improve the transportation system.

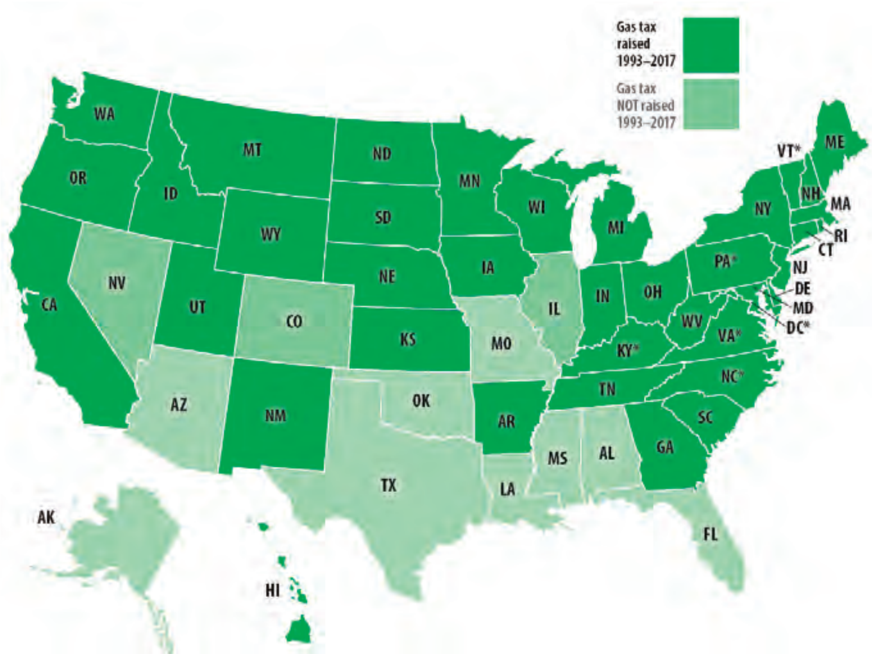

FIGURE 6-3 States that have raised fuel taxes since 1993, when the federal fuel tax was last raised.

approach suggests it could lead to large swings in revenue because of retail fuel price volatility.) Fuel tax revenues, however, are becoming increasingly decoupled from highway use, both because of rising vehicle fuel economy in general and increased use of electric power and alternative "fuels" that are not now subject to federal taxes for transportation purposes. The annual Corporate Average Fuel Economy (CAFE) light duty fleet (automobiles and light trucks) for new vehicles is scheduled to double that of the existing fleet by 2025 (Kirk and Mallett 2018, 2).[6] Whereas these erosion effects are gradual and small on an annual basis, they become quite substantial over the span of a decade or more. Despite these disadvantages, it merits recognition that the federal fuel tax still generates revenues of more than $30 billion annually. Even over a period of years of increasing vehicle fuel economy, the taxes would continue to provide a significant revenue stream

[6] Future CAFE standards are currently being reconsidered. If standards for model years 2021 to 2026 were to be frozen at 2020 level as proposed, and consumers purchased less fuel efficient new vehicles, then fuel tax revenues would increase compared with the existing CAFE requirements. Without certainty about when or whether the proposed changes to CAFE standards would be modified, the analyses in this chapter are based on the current standards.

(though diminishing over time) that could be dedicated to specific aspects of the highway federal-aid program.

Regarding income, fuel taxes are regressive; lower income motorists pay a higher proportion of their income for fuel when they drive than do higher income motorists. Geographic equity depends on how the revenues are allocated relative to where they were generated, which is relevant to other funding options as well. Although gas taxes are perceived as fair because they relate consumption of highway use to taxes paid, unlike a toll that applies to a specific facility, the fuel tax generates revenues from motorists using the entire road system, and it can be difficult to assure that the revenues from the tax will be spent on the road systems where most of the fuel combustion took place.

Truck Taxes

Federal taxes other than fuel taxes whose revenues are dedicated to the HTF include the existing heavy vehicle use tax (HVUT), heavy truck and trailer sales taxes, and a tax on truck tires (see Appendix J). Collectively, these taxes contribute about 13 percent of total user-fee revenues to the HTF, most of which is derived from the sales tax on trucks and trailers. The HVUT and tire taxes increase with the rated weight of the vehicle, which is intended to correspond to the damage that heavy commercial trucks impose on pavements and bridges. For example, pavement damage associated with load rises exponentially (roughly at the third power); hence, the heaviest vehicles impose a vastly disproportionate share of wear and tear on highway infrastructure compared with the lightest vehicles (Small and Winston 1989). In addition, there are inequities in the incidence of the levies within and across classes of vehicles. For example, the current federal rates (analyzed by the Federal Highway Administration [FHWA]), result in pick-up trucks and vans significantly overpaying for their cost impact on federal-aid highways, as do heavy trucks weighing 50,000 lb. to 70,000 lb., with the heaviest trucks (more than 75,000 lb.) significantly underpaying for their share of the damage they cause.[7] The share that commercial trucks would need to pay to equitably balance their impact on highways across truck classes has been estimated periodically by FHWA in cost allocation studies.

Pros: Both national commissions noted that the HVUT has not been increased since 1983 (35 years at the time of the present report) and recommend that it be adjusted to account for inflation and increased heavy truck

[7] FHWA periodically assesses the damage that classes of vehicles cause to highways through cost allocation studies. The last study was completed in 1997, but updated in 2000 with an addendum. See FHWA (2000, Table 7) for estimated payment based on damage caused by class and weight.

travel. The tire tax is an amount that varies across weight categories that applies to specific vehicle weight ratings. Truck and trailer taxes are sales taxes that rise with the value of the goods sold. Collectively, these taxes have considerable revenue potential but most of the revenue would come from the HVUT and the truck/trailer tax. The Finance Commission estimates that a 50 percent increase in revenues from the HVUT would yield an additional $500 million to the HTF, a 10 percent increase in revenues from the truck/trailer tax could raise $330 million annually, and a 10 percent increase in revenues from the tire tax would raise only $4 million annually (see Appendix J). The Finance Commission noted compliance and enforcement costs of truck/trailer and tire sales taxes are minimal, but that there have been occasional evasion issues with the HVUT.

Cons: The SAFETEA-LU Finance Commission indicated that there are disadvantages with raising additional highway revenues through the existing tax structure. The HVUT is subject to evasion and this might increase if the fee were increased substantially. Truck and trailer sales taxes already account for 12 percent of the purchase price of new vehicles and trailers, thus an increase large enough to generate substantially more revenue would likely face significant opposition. Finally, truck tire taxes generate little revenue.

Moreover, as indicated, some classes of trucks overpay for their share of pavement and bridge damage, whereas the heaviest vehicles underpay. Both efficiency and equity arguments can be made for correcting these rates of miss-payment. The tax on diesel fuel by itself does not fully capture the exponential effects of truck axle weights on infrastructure wear and tear, thus a tax that reflects pavement and bridge loadings can be argued as appropriate. The most recent Highway Cost Allocation study (FHWA 1997) conducted by FHWA was last revised in the year 2000 and warrants updating to reflect the character of the current fleet and the share of highway costs attributable to different classes of vehicles.

Institutional and Policy Considerations

Federal motor fuel and truck taxes currently dedicated to the HTF include important incentives to increase efficiency and, for the most part, have relatively minor enforcement and compliance costs. States also depend heavily on fuel taxes for their own highway investments. Fuel taxes, as fixed-rate excise taxes, have the disadvantage of not rising over time to account for inflation and increasing vehicle fuel economy, but this could be addressed through indexing. Their revenue potential will continue to erode over time as fuel economy improves, but they will still offer very significant revenue potential over the coming decade or so. Keeping the share of taxes that trucks pay consistent with the costs they impose on the system is important for both efficiency and equity reasons.

Federal fuel taxes and truck taxes are integral parts of the existing federal–state partnership for funding highways that serve state and interstate travel and increases in fuel and other related taxes would build on this long-standing relationship. The share of federal tax revenues from fuel and truck taxes allocated to Interstates by the states (31 percent) is consistent with the share of federal fuel tax revenues generated by Interstate travel (29 percent) (derived from FHWA [2015, Table VM-1; 2016a, Table FA-4C]). Raising fuel and truck taxes specifically for Interstate investment may prove challenging, as the public may not accept a tax policy that requires users of all roads and highways to pay disproportionately more for Interstate renewal and modernization relative to their use of the system.

Adjusting upward those federal taxes that apply to the heaviest vehicles would continue to serve the policy goal of all users paying for the infrastructure damage they cause, and set a standard that states could follow with their own taxes and fees. An updated federal cost allocation study to determine appropriate cost responsibility for different classes of highway users is warranted in this regard.

Option 2: Allowing States and Metro Areas to Toll Existing General-Purpose Interstate Highways

Tolls on Interstate highways could provide the revenue stream needed to repay debt incurred to improve the Interstate Highway System. In southern Europe and Japan, tolling is prevalent for financing motorways (roughly equivalent in concept to U.S. interstates) (see Appendix J). MBUFs, a type of toll described in the next section, are increasingly common in northern Europe for heavy truck use of motorways and other major national highways (see Appendix J; Doll et al. 2017). However, in the United States, when federal funding for highways began in 1916, the authorizing legislation included a blanket prohibition on tolling highways supported with federal funds. Subsequently, many exceptions were allowed, particularly in recent years as fuel tax revenues fell short of funding federal-aid program authorized by Congress (Kirk 2017, ii).

As a system, the Interstates have the highest volumes of any class of U.S. highways, so if the practice of tolling to generate revenue would be effective anywhere, its promise would seem to be greatest on the Interstates, particularly high-volume congested urban segments. Indeed, 60 percent of current U.S. toll roads are on the Interstate System and the number of tolled miles is growing—750 miles of tolled highways, bridges, and tunnels were converted or added to the Interstate Highway System between 1990 and 2015 (Kirk 2017, 10). Federal restrictions on tolling, however, are most applicable to Interstates (as explained below). If those restrictions were lifted, toll options for Interstate highways could be introduced gradually in a variety of ways. Tolling is already permitted on any new segments of highway mileage added to the Interstates. If tolls could be collected to pay for the reconstruction of *existing* Interstate mileage, a system of tolled Interstates would emerge over time, the development of which could be accelerated through bonding tied to toll revenue streams and public–private partnerships (Poole 2013).

The revenue potential from tolling is substantial. Poole (2013) estimates that, in aggregate, tolls somewhat below the average rate per mile charged on existing long-distance toll roads could pay for the roughly $1 trillion investment that would be needed to widen and reconstruct the Interstates. (This $1 trillion estimate is generally consistent with the 20-year, $45 billion to $70 billion per year scenario to renew and modernize the Interstates described in Chapter 5.) Poole's analysis indicates that toll rates for passenger cars and light trucks (in 2010 dollars) would be 3.5 cents per mile and 14 cents per mile for heavy trucks, compared with then existing average rates on long-distance toll roads of 4.9 cents per mile for passenger vehicles and 19.9 cents per mile for heavy trucks.

Pros: Tolling targets specific consumers' use of specific highways, tunnels, or bridges, thereby encouraging efficient use and allocation of such assets. It also allocates costs to the system's beneficiaries. Although only a small share of highway facilities is tolled currently (0.6 percent of federal aid-eligible highway mileage (centerline) [Kirk 2017, 9]), 7 percent of the Interstate System mileage is tolled, including very prominent sections such as major bridges and tunnels on the East and West coasts and turnpikes in the Northeast and Midwest. In addition, the existing roughly 40 High-Occupancy Toll (HOT) and Express lanes,[8] most of which are on Interstates, are expanding awareness of toll options and acceptance of tolls on Interstates. The majority of public opinion polls show majority support for tolls compared with other alternatives such as higher fuel taxes, and support grows with familiarity with toll roads, when funds collected are dedicated to specific highway improvements, and as an alternative to other forms of taxes to support highways (Zmud 2008; see also Zmud and Arce 2006). Interstate tolls would likely cause some shifts in motorist behavior, including the time, routes, and modes selected for travel, and could cause a small amount of truck freight to shift to rail at a net social benefit (Austin 2015).

Cons: Most evidence indicates that tolls are more complicated and costly to collect than fuel taxes. Even for the toll roads that have extensive electronic tolling, Kirk (2017, Table 1, 7) reports that collection costs

[8] See https://managedlanes.files.wordpress.com/2017/07/0-ml-database-green-yellow-blue-key-march-2017.pdf.

consume 8 to 13 percent of gross revenue. However, Fleming and colleagues (2012) argue that toll roads using all-electronic tolling (and only allow payment by credit card) have reduced collection costs to 5 percent. Fleming and colleagues (2012) also argue that there are hidden costs in the collection of fuel taxes (e.g., the administrative costs of collecting and reporting these taxes incurred by distributors and retailers). When accounted for, according to these authors the difference between the collection cost of motor fuels taxes and all-electronic tolling is small. However, there would be a substantial cost to add toll-collection technology to existing Interstates.[9]

Although the estimates show that tolling rates required to fund renewal and modernization of the Interstates, on average, would be below rates on existing toll roads, rates would need to be higher on urban routes sustaining high improvement costs. Moreover, rates on some rural routes with light traffic would be too high to be practicable (Poole 2013, Appendix A). He estimates that six rural states would likely be unable to fully fund their Interstates with reasonable tolls and would require additional federal aid or state funds.

The motor carrier industry has expressed strong opposition to toll roads, although its argument about the high administrative cost of toll collection is not indicative of the efficiencies achieved by advances in toll collection technology (Short 2017). Independent owner-operators would be particularly affected unless shippers agreed to begin reimbursing them for tolls (Wood 2011). Tolling might, however, encourage heavy trucks to divert to untolled routes that could be less safe and are less prepared to accommodate large loads. Studies of route diversions and their consequences are fairly scarce. Studies based on measured route diversions on the Ohio Turnpike following toll rate increases indicate that the results of increased crashes could outweigh the economic benefits of tolling (see Swan and Belzer 2010, 2012). Diversions of passenger traffic to other highways in order to avoid Interstate tolls could also adversely affect safety and congestion.

Tolling also raises equity concerns—as tolls fall proportionately more heavily on those with low incomes—although these concerns can be alleviated in part by using some of the toll revenue to support alternatives such as public transportation, as is done in most express lane high-occupancy vehicle toll (HOT) arrangements. Opposition to tolling includes the issue of

[9] As cited in Poole (2013, 14), Fleming, an electronic tolling expert, estimates a cost of converting existing rural Interstate miles to an all-electronic tolling system at $250,000 per mile and urban Interstates at $2.5 million per mile. For the 48,473-mile Interstate System, this indicates a conversion cost on the order of about $7.3 billion for rural Interstates and $48.2 billion for urban Interstates, for a total of roughly $55.5 billion. Whereas these are large figures, so is the amount of travel. For urban Interstates, the 525 billion miles of annual VMT would pay for the conversion cost at less than 1 cent per vehicle mile over 10 years.

"double-taxation," whereby users pay both a fuel tax and a toll, although the rationale for using only one type of funding mechanism to achieve a given revenue stream is not obvious and there are means by which this specific concern could be addressed. For example, fuel taxes paid on toll facilities could be rebated to consumers, although this would increase the administrative cost of tolling. In addition, a more widespread system of tolls, even if limited to urban Interstates, could raise the need for federal regulation to keep states from setting tolls that unduly impede flows of interstate commerce. (Existing regulations restrict toll revenues collected from users of federal-aid highways from being diverted by states or local governments for non-transportation purposes, but do not address the toll rates themselves.) Finally, whereas Congress has expanded the ability to toll federal-aid highways over the years, it has been reluctant to ease restrictions on tolling of existing Interstate lane-miles.[10]

Institutional and Policy Considerations

Financing Interstate reconstruction and widening through tolls could encourage efficient use of the Interstates and better align projected increases in travel demand with system capacity. It would, however, entail major changes in institutional relationships between the federal government and the states and would impose various other policy trade-offs. If states used toll financing to generate only the revenues needed to pay for improvements to specific segments financed by bonds, funds would not be generated to help pay for improvements to other segments of the Interstates that may be unable to generate substantial revenue through tolls. (In typical bonding arrangements, the funds generated by the facility are restricted to collection and enforcement costs, maintenance, profit, and repaying bond holders.) Therefore, funds would not necessarily be generated to help pay for other segments of the Interstates that may be unable to generate substantial revenue through tolls. A general, wide-spread system of tolls across the Interstates, however, could include a requirement for high-traffic segments to share revenues with low-traffic segments, much as fuel tax revenues are used to subsidize low-volume routes.

Both national commissions cited above encouraged wider use of electronic tolling, but indicated that the potential problem of instituting regulations to prevent charging excessive rates to trucks and through-traffic

[10] The FAST Act allows all new Interstate highways, tunnels, and bridges to be tolled; existing bridges and tunnels to be tolled if reconstructed or replaced; and added lane capacity in existing corridors can be tolled; but the existing toll-free lane-miles must be maintained toll free. Revenues from tolls are distributed among the owners and operators of the toll facilities.

would need to be mitigated.[11] To date Congress has not granted authority to the U.S. Department of Transportation or any other federal agency to regulate toll rates. (Disputed cases are typically adjudicated in the courts.[12]) FHWA does have authority to oversee the use of toll revenues and can veto proposals that divert funds to purposes not consistent with federal law. Federal regulation of toll rate setting would entail a change in legislation to avoid interfering in state and local tolling arrangements, but Congress most likely would have Constitutional authority to do so under the Commerce Clause (Kirk 2017, 14–17).

Although tolling would have the benefit of shifting a modest amount of truck freight to rail, another major policy consideration of tolling involves diversion by truck drivers to untolled roads that can be both substantially less safe than the Interstates and not constructed to withstand the wear and tear of heavy trucks. States and toll authorities can attempt to account for such problems in the setting of toll rates. Avoiding this problem suggests that tolling of the Interstates might need to be accompanied by some form of charging or taxing heavy trucks' use of all highways, as is done in Germany and Switzerland (see Appendix J). This option, however, would greatly expand the complexity of policy issues already encountered.

Addendum: A Hybrid Approach

Possible hybrid approaches to tolling merit consideration. Already mentioned is the option of allowing states to toll existing Interstate segments in need of rebuilding and/or widening. Over time, this could lead to substantially more segments of the Interstates that are funded directly by users. Any proposed upgrades of National Highway System (NHS) routes to Interstates could be required to fund this cost through tolls (this option is already available). Variable tolls, or congestion pricing, could also help urban areas manage demand on existing urban Interstates, which may be particularly important in areas with extremely high expansion costs. To address equity concerns, some of the revenues earned could be used to provide transit alternatives, as is done in many HOT-lane and express lane projects. Allowing states or metropolitan areas to toll existing lanes after rebuilding would require a change in law by Congress.

[11] The Policy Commission recommends that Congress set strict criteria for the imposition of tolls on Interstate highways, including a requirement that "rates be set so as to avoid discrimination against Interstate travelers or any other group of users" (National Surface Transportation Policy and Revenue Study Commission 2007, 47).

[12] See Kirk (2017, 14–17) for a review of court interpretations of the Commerce Clause.

Option 3: Instituting Mileage-Based User Fees for Interstate Use to Replace Other User Fees

The SAFETEA-LU national commission reports both recommend evaluating and moving toward VMT fees to ultimately replace motor fuels taxes. Since those reports were published in 2007 and 2009, the term "VMT fee" has been replaced by "mileage-based user fees" (MBUFs) in the United States. MBUFs are revenue-raising mechanisms similar to tolls, but without tollbooths. The concept is to charge users for the distance they travel, which could range from basing the charge on odometer readings to using more complex approaches (some using GPS) that would allow charges to be based on type of road, fuel economy, and road wear (with vehicle weight being a proxy) among a range of other possibilities. An important distinction between a typical toll (which is often distance-based) and MBUF is that tolls are typically used to repay bond holders. Revenues from MBUFs could do the same, but could also generate funds for the HTF that would not be tied to a specific facility but could be dedicated to the Interstates.

MBUFs are a relatively new approach for most of the motoring public, but experimentation with, and evaluation of, the concept has been under way for more than a decade in the United States (two decades in the case of Oregon) and several new pilot projects are under way at the time of this writing (see Appendix J). In addition, variations on MBUFs are in place in some European countries (for heavy trucks) and have been used for many years in New Zealand (for trucks and cars using diesel fuel) (see Appendix J).[13] A federally supported, state-applied MBUF could one day replace motor fuels taxes and the revenues currently used to support the Interstates as well as the rest of the federal-aid highways. In the FAST Act of 2016, Congress approved a $92 million pilot program in which many states are participating, as described in Appendix J.

Interstate Mileage-Based User Fees

A two-pronged proposal has been put forward by Schenendorf and Bell (2011) for an Interstate-specific MBUF that could be implemented for passenger vehicles with existing technology would require trucks to use

[13] According to Kirk and Levinson (2016), Switzerland, Germany, and Austria, among a few other European Union member countries, impose per mile fees on heavy trucks crossing national borders that can be as high as $1.33/mile for a heavy truck in Switzerland and range from 20 to 82 cents per mile in Germany and Austria. Switzerland's fees are designed to encourage modal shift of through traffic to rail. In lieu of a diesel tax to support road use, New Zealand has charged a MBUF for diesel fueled trucks and cars since 1977. The fee is designed to reflect the marginal cost of road wear. Truck fees can be as high as 40 cents per mile and fees for passenger vehicles are about 7 cents per mile, roughly equivalent to what a gasoline-powered vehicle would pay (see Kirk and Levinson 2016, 10–17).

similar systems on all roads. In this proposal, passenger and freight users of the Interstates would be required to have an electronic transponder, such as used by E-ZPass, TxTag, Fastrack, and other vendors, to gain access. Users would then be charged a mileage fee upon exit. Interstate access and exit ramps would be retrofitted with gantries such as those used by toll roads with electronic charging. In order to avoid the problem of trucks diverting to non-Interstate highways free of tolls but not suitable for such traffic, trucks would be charged for use of all roads. This can be done by deploying GPS-based systems or other similar systems such as those large carriers already use in their fleets to monitor driver and truck performance. This proposal for trucks would be similar to the systems used in Austria, Germany, and Switzerland that charge trucks for use of motorways and other main highways (see Appendix J).

Funds collected from Interstate users would be provided to the states for Interstate maintenance and upgrades and allocated in a fashion similar to the present federal-aid program. Fees collected from motor carriers operating off the Interstates would be used to fund freight intermodal projects that relieve bottlenecks anywhere on the federal-aid system. Under this plan Congress would establish an independent body to annually set fees that would vary with geography. Other than these revisions, the authors state that their proposal would not change the rest of the federal-aid program or the existing user fees imposed.

If this option were pursued, the amount of additional revenue that would needed to renew and modernize the Interstates would be higher than the levels estimated in Chapter 5 because of the cost of converting the Interstates to all-electronic tolling (AET) system. This one-time investment, as estimated above, would be about $55 billion. For simplicity, it is assumed this investment would have a replacement cycle of 10 years and would be amortized over that period; hence adding $5.5 billion per year to the cost of converting the Interstate System to AET. The cost of administration is estimated to be 10 percent of revenues earned (or another $2–$3 billion annually). As a result of converting to AET and administrative costs, about $28 billion in revenue would be required to raise $20 billion in new revenue for Interstate renewal and modernization. As described in Appendix J, the approximate per mile fee required for passenger cars to produce such revenues would need to be 2.7 cents per mile. Truck rates would be approximately 3.3 cents per mile. By way of comparison, these rates would be lower than the per-mile equivalent tolls currently charged on urban and rural Interstate toll roads, which average about 8 cents per mile for passenger cars and 30 cents per mile for trucks (see Appendix J).

Pros: Directly charging for the use of the Interstates would enhance throughput efficiency and help manage demand by shifting some traffic to the off-peak or other modes. Shifting more freight from highways to rail could be socially beneficial (Austin 2015). Requiring users of the system to pay for road use would be equitable across highway users in terms of paying their fair share, but would be more burdensome to low income users. The existing system of electronic toll collection is well established and accepted by most motorists, with a proven system of billing. Acceptance by interstate truck operators, however, is another matter.

Such a system would not track passenger vehicle drivers' entire trips, as would a full-scale MBUF, thereby mitigating privacy concerns, but would record entries-to and exits-from the Interstate Highway System. It could be implemented within a few years, far sooner than a general MBUF, albeit with a significant investment (about $55 billion). As proposed by the authors of this concept, the revenues generated from the Interstate MBUF would be returned to the HTF and redistributed to states for Interstate improvements on a "pay-as-you-go" basis. Doing so would address the cross-subsidy that would be necessary to fund rural Interstate segments that could not be self-supporting through MBUFs.

The proposed two-pronged approach would avoid the problem of trucks diverting from Interstates to other NHS routes or state roads to avoid paying a mileage fee, and it would create a self-sustaining fund for renewing and modernizing the Interstates. It would also create a specific fund for addressing intermodal freight bottlenecks that have proven particularly difficult for Congress to address in recent reauthorizations of surface transportation legislation. The federal fuel taxes and other user fees would remain in place and would be used for non-Interstate federal-aid highways. This could potentially depoliticize rate setting. If a MBUF worked for the Interstates, it could be a model for a system of MBUFs that could, in time, replace, rather than supplement, motor fuel taxes.

Cons: Whereas electronic billing is accepted by many highway users, a substantial proportion of toll-road users prefer to pay in cash and most U.S. highway users do not use AET charging toll roads on a regular basis. Thus, general familiarity with, and acceptance of, an all-electronic charging approach is not ensured. Previous surveys indicate relatively little public awareness or understanding of MBUFs and, to the extent it is understood, offer little support for MBUFs as a replacement for fuel taxes (Agrawal et al. 2016).[14] Collection costs could consume a greater share of the revenue acquired than fuel taxes, although an AET system, if possible, would narrow the difference considerably. (Estimates of the cost of collecting MBUFs are in the range of 5 to 13 percent compared with about 1 percent for the

[14] Note that the surveys summarized in this report were conducted before the MBUF pilot programs funded through the FAST Act were initiated. One purpose of these pilot projects is to increase public awareness and understanding of the concept, as described in Appendix J.

fuel tax [Kirk and Levinson 2016, 4; see also Appendix J].[15]) An AET approach, however, may not be acceptable to the public. To include those without access to banks and credit cards would require an alternate means of paying, which would further increase cost. Although many trucks are already outfitted with technologies that would allow charging mileage fees while off the Interstates, a substantial proportion of heavy trucks (about 10 percent) (U.S. Special Delivery 2017) are operated by independent owner-operators who would undoubtedly resist the added cost, and potential scrutiny, of their operations—much as they have long opposed electronic log books. The motor carrier industry overall could be expected to strongly oppose an MBUF that charged trucks for highway use. As with tolling, shifting of passenger traffic to alternate highways to avoid the fee could adversely affect safety and congestion on those routes.

Institutional and Policy Considerations

The Schenendorf/Bell proposal retains much of the existing federal–state partnership, thus funding the Interstates on a pay-as-you-go basis through an MBUF would not entail substantial institutional change. The viability of some elements of the proposal, however, are questionable, including the public acceptability of an independent body to set rates. Given the great diversity within the country, designing a fee that would vary by geography and be adjusted annually and be perceived as fair and acceptable, while also generating sufficient revenue, would be a challenge for any organization. Thus, composition of the proposed independent rate-setting body and the appointment process could be highly charged politically. Moreover, Congress may be loath to defer to an independent authority to set rates affecting its constituents, and if Congress retained the right to review and veto the independent authority's decisions on rates, as it does with the analogous Postal Regulatory Commission, the process could be almost as difficult as approving fuel tax increases. This problem could potentially be addressed by having Congress set the fee initially, based on estimated revenue needs, and then allowing the rate to be adjusted annually by some measure of inflation.

Although the authors argue that their proposal would not affect the basic structure of the federal-aid highway program, it would require some changes. For example, a new means of allocating Interstate fees collected from users back to the states would be necessary, since the existing federal-aid program does not set aside funds for the Interstates nor allocate federal aid for the Interstates to the states on the basis of Interstate usage.

[15] Germany's cost of collection is about 13 percent and New Zealand's is about 2.5 percent, but New Zealand's system has higher evasion rates than Germany's and New Zealand does not have to address substantial cross-border truck traffic.

The proposal to add a mileage fee to trucks for use of all roads could have ramifications for the share of freight moving on highways compared with rail. For a 500-mile trip today, the typical truck pays about $19 in federal diesel taxes. The cost of such trips that would be needed to provide an additional $20 billion annually beyond today's revenues (for the purpose of renewing and modernizing the Interstates) would be about $55. As a result of such additional costs, some freight would shift to rail and some would continue to use highways, but at a higher cost to motor carriers, shippers and, eventually, consumers.[16]

OTHER FUNDING OPTIONS

At a Glance

In addition to the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users commissions' recommendations, Congress might consider policies for providing the funds needed to renew and modernize the Interstates that do not involve new or revised user fees, including

- Dedicating more of existing federal aid to the Interstates;
- Continuing the status quo (with General Fund transfers); and
- Applying a carbon tax or cap-and-trade fees in part to highway funding (as a potential future strategy).

While an investment of $20 billion or more per year to renew and modernize the Interstates would seem implausible in the absence of new user-based revenues sources, as discussed above, Congress could consider options for funding at least part of this investment. For example, Congress might consider policies that do not involve new or revised user fees. This section reviews three such options: (1) giving states less discretion over their federal aid and allocating a larger share of existing federal aid to the Interstates; (2) continuing to rely on General Fund transfers to make up for shortfalls in revenues from motor fuels and other taxes dedicated to the HTF; and (3) over the longer term, using revenues from carbon taxes and cap-and-trade programs as supplemental funding sources were Congress to implement such taxes and programs.

[16] The shift to rail would not necessarily be large. A recent working paper from the Congressional Budget Office estimates that truck rates of greater magnitudes than those described herein would cause about 3 percent of truck freight to shift to rail (see Austin 2015).

Option 4: Dedicating More of Existing Federal Aid to the Interstates

If it proves impracticable to raise user fees significantly to sustain the Interstates, one option would be to shift federal-aid funding eligibility in favor of greater investment in the Interstate System at the expense of other programs. In recent federal surface transportation authorizations, Congress has moved away from funding specific highway systems to more of a "block grant" approach, in which states have a great deal of discretion in the types of projects to which funds are allocated, as long as they are devoted to eligible facilities. In the FAST Act, Congress authorized $43 billion in fiscal year 2016 to contract authority for highways, an amount that increases to about $47 billion in fiscal year 2020. Of this amount, about $35 billion annually, on average, under the FAST Act is made available to the states for a broad set of improvements to eligible highways, including the Interstates, NHS, and for transit improvements (FHWA n.d.). As noted previously, in 2014, the most recent year for which data are available, states obligated about $11.2 billion of their federal-aid funds to the Interstate Highway System out of $35.4 billion (31 percent). Note that many states spend considerably more on their Interstates than the federal aid they allocate. Total state outlays on Interstates in 2014 were $29 billion (including capital investments and maintenance costs), making the state share 62 percent compared with a federal funding share of 38 percent (FHWA 2016b). This reflects the focus on maintenance as opposed to new construction for which the federal/state share is 90/10.

Pros: The Interstates represent the most important highways for moving interstate commerce and arguably should, in general, be of greatest priority among various highway classes. Supporting an Interstate System that connects the entire country with high-quality controlled-access Interstate highways was the original purpose in creating the HTF and federal-aid program. Relying on existing user fees would avoid the cost and disruption of converting the Interstates to toll roads or for collecting MBUFs.

Cons: The main disadvantage of the reallocation of resources approach is that, depending on the rate of VMT growth and the investment required to renew and modernize the Interstates, it could consume half (in the $45 billion annual Interstate re-investment case) to more than the entire amount of current federal highway aid to states (in the case of the $70 billion case) to meet the future funding needs of the Interstates. If so, this would require states to spend more of their state-generated revenues on the rest of the federal-aid highways, including routes that are primarily interstate in function. Moreover, because the transportation system is a network, it can be difficult to separate national from local interests. For example, many routes on the NHS serve as essential feeders onto the Interstates and, to the extent that transit funding moves local traffic off of the Interstates and other NHS routes during peak periods, it frees up these highways for through traffic.

Institutional and Policy Considerations

Because of the likely magnitude of funds needed for renewing and modernizing the Interstate Highway System, reallocating more federal aid for this specific purpose would not be sufficient overall if the required Interstate investment significantly exceeded $40 billion per year. Although the existing federal funds could be sufficient for the Interstates, the rest of the federal-aid highways, many routes of which serve as important connectors to the Interstates, would have to be funded by states alone—which could have broad implications for the future of the federal-aid highways and the connectivity it provides.

Option 5: Continue Status Quo (with General Fund Transfers)

As indicated in the introduction to this chapter, in recent reauthorizations of surface transportation legislation, Congress has opted to increase transfers from the General Fund rather than increase motor fuels taxes or other user-type fees. In the deficit budget context of recent years, this implies that the supplemental funding is acquired through Treasury borrowing.

Pros: The advantages of relying on borrowing are that it maintains the status quo, avoids the problems associated with raising user fees, and, at least in the recent past, has made substantial funding available for the federal-aid highways. Furthermore, Congress has long used the General Fund for other transportation purposes, such as public transportation and bicycle lanes.

Cons: Transfers from the General Fund, made possible by borrowing, is a hidden tax on the economy and ultimately on the general public. Government borrowing during periods of economic growth drives up interest rates and potentially crowds out access to capital from its most critical potential uses. Borrowing to pay for highway infrastructure and repaying through general taxes also undermines opportunities to enhance efficiency. Users perceive that use of highways is underpriced relative to the benefits they receive and therefore are encouraged to overconsume highway travel. Moreover, the trend is unsustainable. The federal government in 2018 enacted tax cuts that will increase the aggregate deficit, potentially by as much as $1 trillion, and thereby further increase pressure to reduce reliance on the General Fund to provide funds for the rest of the discretionary budget (CBO 2018). In addition, as more General Fund revenue is allocated to the HTF, it raises equity concerns. Some large urban states contribute substantially more to the General Fund than they receive back in total federal spending at the state level. As the General Fund contribution to the HTF grows, the "donor" states to the federal treasury may be expected to exert pressure for HTF allocations to match individual states' contributions to the General Fund.

Institutional and Policy Considerations

A combined system of partial reliance on user fees and increased transfers from the General Fund would continue to sustain the federal–state partnership on highways, since, other than the transfers, the rest of the institutional relationship remains intact. Asking for an additional $20 billion or more per year for an Interstate rebuilding program without expecting highway users to pay for it directly, however, may well be unacceptable to the public. Moreover, it could further sever the tradition of funding the federal-aid highway program through user fees, which has already become tenuous because of the increasing scale of General Fund transfers to the HTF in recent years.

Option 6: Applying Carbon Tax or Cap-and-Trade Fees in Part to Highway Funding (as a Potential Future Strategy)

Many national governments and states are considering either carbon taxes or cap-and-trade programs as they grapple with controlling carbon emissions from transportation (see Appendix J). The implementation of these strategies differ: their principal effect of taxing or pricing carbon emissions would be to discourage use of fossil fuels, which, depending on size of the tax or price, could have a profound effect on transportation because of its heavy reliance on petroleum-based fuels. In the near term, pricing or taxing carbon would surely reduce demand on Interstate highways and shift more traffic to other modes. Over the longer term, requiring transportation to internalize the cost of carbon emissions would facilitate shifts to alternative fuels and electrification of the vehicle fleet and possibly re-balance the shares of freight moved by highway, rail, and water. During the transition to alternative fuels and modes, both carbon taxes and cap-and-trade revenues would generate substantial new revenues as many highway users would have little choice but to pay higher fees or taxes until alternatives could be found. It would be speculative at this point in time to estimate potential revenue sources from taxing or pricing carbon or how such revenues might be used. California's cap-and-trade program provides some insight about the latter.

California currently dedicates some of the revenues earned from its cap-and-trade program to transportation, but not to highway facilities. A case could be made, however, for dedicating some future carbon tax or cap-and-trade revenues to the Interstates to facilitate adoption of zero- or low-carbon emission electric-drive technologies, including hydrogen fuel cells. For example, such revenues could be used to subsidize the cost of recharging and refueling stations (as is the case in California [Green 2018]), the lack of which is an impediment to more wide-spread adoption of zero- or low-emission vehicles in intercity transportation. It is not possible to forecast what national or state policies might be adopted in the future regarding controlling transportation carbon emissions, but as some states follow California's lead with cap-and-trade programs, creative options that are not apparent or politically acceptable currently may emerge and be suitable for renewing the Interstate system.

SUMMARY

Key points regarding application of the funding options detailed in this chapter are summarized below.

Combining funding options. Fuel taxes today generate 87 percent of the revenues for the Highway Trust Fund, but are a declining revenue source as internal combustion vehicles become more fuel-efficient and will decline precipitously as electric vehicles become commonplace. There are no easily implemented choices for funding Interstate renewal and modernization, but combining options, phased in and out over time, is a promising approach. As the two national commissions established by Congress concluded one decade ago, few options can generate sufficient funds to pay for rebuilding and expanding the Interstate System while meeting other appropriate criteria; rather, all options have advantages and disadvantages. Given the magnitude of the funds needed for the Interstates and the importance of the system to the overall economy of the nation, a promising option is to combine elements of some of the options described herein to maximize the advantages and minimize the disadvantages of each.

Relying on user fees. Highway programs have long been funded by user fees that have both efficiency and equity merits. Only a limited number of revenue sources can generate the $35 billion or more in federal aid now devoted annually to the overall federal-aid highways. A combination of increasing motor fuel taxes and highway user fees, allowing states and metropolitan areas to impose tolls on selected segments of existing Interstates, and instituting Interstate-specific user fees could raise substantial funds for Interstate renewal and modernization and help state and local jurisdictions manage highway demand.

Increasing user fees. Increasing motor fuel taxes and other user fees would have advantages, especially for the near term. Fuel taxes have long been the principal source of federal highway funding and have been an effective, efficient, and equitable form of user-fee funding for decades. These fees, however, are far past due for an increase to account for inflation, rising fuel economy, and increased use of highways. Congress could address the disadvantages of the current flat taxes (e.g., gasoline and diesel taxes) by indexing them to inflation and increases in fuel economy and phase in tax increases over time as an Interstate renewal and modernization effort expanded. Given the nature of the federal-aid program as it has evolved over the decades and the diminishing use of fuel with an electric-drive fleet, dedicating any resources derived from any increased fuel taxes to the Interstates may have to be a part of a strategy for increasing Interstate funding in the near term.

Phasing in higher taxes and increasing fees paid by heavy trucks. The Interstates benefit everyone directly or indirectly and were originally funded to reflect this relationship, and increasing fuel taxes represents a reasonable near-term option until other revenue sources can be developed. If motor fuel taxes are increased, it would be appropriate to consider phasing in the higher taxes and increasing the Heavy Vehicle Use Tax and other fees paid by heavy trucks at the same time so as to ensure that all users pay a share that fully reflects the costs they impose on the system. A new federal cost-allocation study is warranted to address this approach.

Allowing states to impose tolls on Interstate segments. States would benefit from having the option to impose tolls, with the receipts being used to rebuild and improve existing high-cost Interstate segments and manage demand on routes too costly to expand. Tolling has a long history in the United States, and about 7 percent of the Interstate System is already tolled. Tolling to finance freeways is common in southern Europe and Japan, and the Interstate System is a prime target for greater reliance on tolls, in part because of its high share of total highway travel. Tolls supplemented with additional fees for congestion, as used in many HOT lane and express lane projects in urban areas, would provide a means of managing demand and encouraging local traffic to remain on local routes, although expanded use of tolling for the Interstates would likely require some form of federal oversight to avoid discriminatory charges to out-of-state users. Current federal restrictions on tolling of existing Interstate mileage are a major impediment to expanded reliance on tolls and congestion fees for the Interstate Highway System. As described earlier, average toll rates needed to rebuild and widen the Interstates would be similar to the tolls charged on existing toll roads. A potential disadvantage of tolling the Interstates is the diversion of truck traffic to highways that are less safe and not designed to handle heavy volumes of truck traffic. Thus, tolling of the Interstates might need to be accompanied by some general mileage-based fee or other form of broad user fee for trucks that would discourage route diversion.

Implementing an Interstate user fee. Highway programs have long been funded by user fees that have both efficiency and equity merits. A mileage-based user fee for the Interstates would enhance efficiency and could replace motor fuel taxes. Revenues gained would be returned to the states for Interstate renewal and modernization on a pay-as-you-go[17] basis. A promising proposal for an Interstate mileage-based user fee includes a requirement that trucks pay a mileage-based fee for use of all roads to avoid the problem of traffic diversion and to generate revenues to address major bottlenecks on all road systems affecting truck travel. Although the added cost of administration and to provide gantries for electronic fee charging to the Interstates is not trivial, this cost could be recovered in about 10 years and paid for by charging all vehicles 1 cent per mile. Furthermore, the per-mile rates necessary for passenger cars and trucks to raise an additional $20 billion annually to renew and modernize the Interstate System are within the range of equivalent per-mile tolls currently charged on Interstate toll roads.

Increasing the share of the federal-aid system allocated to renewing and modernizing the Interstates. Reallocation of existing federal aid for Interstate renewal and modernization would avoid having to raise taxes or impose new fees, but from half to more than all of existing federal aid may be required for Interstate renewal and modernization, thereby shifting the burden to states for the rest of the federal-aid highways. The current federal-aid highway program, which allows states considerable discretion in how federal aid is invested, results in about 30 percent of available federal aid being spent on the Interstate System—roughly $11–$12 billion annually. Given the importance of the system for interstate travel and commerce, the federal government could require greater emphasis on Interstate rebuilding, maintenance, and expansion. Doing so would avoid the problem of raising motor fuel taxes and the cost and disruption of modifying the Interstates so as to rely on tolls or mileage-based user fees. The disadvantage of this approach is two-fold. First, the annual cost of renewing and modernizing the Interstates could require a minimum of half and a maximum of more than the entire existing federal-aid highway funding. Second, shifting such shares of existing federal aid to the Interstates would burden states with applying more state funds to sustain the rest of the federal-aid highways.

Using General Fund revenues. Continuing to pay for a portion of federal highway aid through Treasury borrowing is a hidden tax on the economy and the public that could diminish future economic growth. Because of reluctance to raise federal motor fuel taxes and other fees for more than 25 years, Congress has met the demands for federal highway aid by increasingly transferring money from the General Fund to the HTF. In light of the recently reduced revenues to the federal treasury due to passage of a substantial cut in federal corporate, income, and other taxes,

[17] The pay-as-you-go approach means that revenues are apportioned to the states only as fast as they come in.

increasingly difficult choices are now confronted, especially concerning how to pay for the discretionary parts of the federal budget. A sound argument can be made that using General Fund revenues is an appropriate way for Congress to pay for routes in rural states that are essential to the overall transportation network and carry mostly through-state travel. A weaker argument can be made for using those revenues to pay for highways when user fees would be more efficient, and demand is adequate to provide the needed funds. Increased borrowing to pay for highways with the General Fund also risks crowding out access to capital in the rest of the economy and thereby diminishing future economic growth.

Using revenues from pricing or taxing carbon emissions. Imposition of a carbon tax or pricing carbon emissions through a carbon cap-and-trade program could generate substantial new revenues for transportation, many of which would come from highway users because of the mode's heavy reliance on fossil fuels. The most immediate effects of taxing or pricing carbon emissions would be to reduce Interstate traffic and shift some freight to less carbon-intensive modes. In the future, and as more states follow California's lead in implementing cap-and-trade programs, a case could be made for tapping some of the revenues for highways, in general, and for the Interstate System, in particular. Investing in facilities along the Interstate to encourage electrification of intercity travel, for example, could reduce carbon emissions from Interstate users.

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Abbreviations

AAA	American Automobile Association
ATA	American Trucking Associations
CBO	Congressional Budget Office
DOE	U.S. Department of Energy
FHWA	Federal Highway Administration
ITEP	Institute on Taxation and Economic Policy
TRB	Transportation Research Board

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7

A Blueprint for Action

In its call for the study reported herein, Congress specified outputs that could be used to inform its pending and future investment decisions and other policy choices concerning the future of the Interstate Highway System. Specifically, Congress asked for information regarding actions that will be needed to upgrade and restore the system to meet the growing and shifting demands of the 21st century. Informed by consultations with highway users, transportation planners and administrators, and other experts and interested parties and by the application of models and other means for estimating improvements to the system and their cost, the committee formed to conduct the study was asked to make recommendations on the "features, standards, capacity needs, application of technologies, and intergovernmental roles to upgrade the Interstate System" and to advise on any changes in law and resources required to further the recommended actions.

The preceding chapters have described the approach the study committee employed in pursuing its work; explained the choices made in framing the study and focusing on certain issues; and documented the study analyses and findings, including the results of an investment needs analysis and its implications. The findings presented indicate that the study request was timely, as the Interstate Highway System's physical condition and operating performance continue to exhibit deficiencies, and much of the Interstate System is already past due for major reconstruction and modernization as a result of heavy use and the effects of age, exacerbated by escalating use and deferred reinvestment. These deficiencies, moreover, raise serious questions about the system's ability to accommodate the future demands of users, including their eventual ability to capitalize on potentially transformative vehicle technologies, as well as its fundamental resilience in the face of climate change, and the time available to prepare the system to meet the latter challenges is dwindling.

Many segments of the Interstate Highway System are more than 50 years old, subject to much heavier traffic volumes and loadings than anticipated, and operating well beyond their design lives without having undergone major upgrades or reconstruction. These aging and intensely used segments, whose numbers are expected to grow over the next 20 years, are poorly positioned to accommodate even modest projections of future traffic growth, much less the levels of growth actually experienced over the past 50 years. As the country moves deeper into the century and transformations in the vehicle fleet and vulnerabilities due to climate change place new demands on the country's transportation infrastructure, the prospect of an aging and worn system that operates unreliably is concerning. The Interstate System, in short, is too important to the nation's economy and the daily lives of Americans to be allowed to fail in its purpose.

The first section of this chapter summarizes findings presented in earlier chapters about looming challenges that confront decision makers as they contemplate the future of the Interstate Highway System. The magnitude of the estimated investments needed over the next two decades to prepare for and meet these challenges would require a major federal and state commitment. That commitment, in the committee's view, must be federally led, state implemented, and suitably funded as part of an ambitious and sustained national campaign of system renewal and modernization. Charged with making recommendations on needed changes in policy and resources relative to the Interstate Highway System, the committee offers a blueprint for the necessary reinvestment program—one that is aggressive; commences soon; and spans the two decades needed to accomplish its crucial goals, as well as to begin laying the groundwork for succeeding decades.

LOOMING CHALLENGES

Over the years, the Interstate Highway System has conferred enormous benefits on the nation. It provides vital connections and services complementary to the nation's other passenger and freight networks and their nodes, including railroads, marine ports, airports, public transit, and local road systems. Not only has it connected and integrated a transcontinental country, as envisioned by its founders, but it also has been instrumental in shaping and supporting the nation's demographic, economic, spatial, and social development for more than 50 years. Because of its far-reaching demographic, economic, and social importance and its vital role in supporting the national defense, it is critical that the Interstate Highway System be brought to and kept in a state that will allow it to accommodate the nation's changing demographic, economic, climate, and technological landscape. Unless a commitment is made to remedying the deficiencies and preparing for the challenges detailed in this report, there is a very real risk that the system will become increasingly congested; far more costly to operate, maintain, and repair; less safe; incompatible with evolving technology; and vulnerable to the effects of a changing climate and extreme weather. If allowed to persist and grow, these deficiencies risk repercussions across all the passenger and freight modes the system connects with and complements.

The following major challenges must be confronted:

- ***Commencing the enormous task of rebuilding the system's pavements, bridges, and other assets and their foundations before they become unserviceable and less safe.*** Many of the Interstate pavements built in the 1950s and 1960s were designed for 20-year service lives, but have now been in use more than 50 years without reconstruction of their foundations—this despite much higher traffic loadings than initially projected. Even assuming that a pavement structure can last 50 years before requiring full reconstruction, the system's oldest segments are long overdue for this work, and even the majority of the newest Interstate segments, constructed in the 1980s and 1990s, will need to be rebuilt over the next 20 years. As this work is being accomplished, states will also require the increased resources needed to maintain the integrity of their aging Interstate bridges.
- ***Meeting the growing demand for investments in physical capacity, especially on the urban portions of the system, and for more active and innovative management of this capacity in large metropolitan areas that continue to experience most of the country's population and economic growth.*** Large portions of the Interstate System, especially in metropolitan areas, are already congested and have difficulty accommodating the demands of local, interregional, and longer-distance travelers. Urban freeway congestion is a complex issue. Alleviating the problem through physical means, such as lane additions, is an expensive and sometimes impracticable option when system right-of-way is constrained by limited land availability. Even if land can be acquired or existing right-of-way can be used more intensively, urban areas are expensive construction environments, and proposals for capacity expansion are often met with opposition because of environmental and community impacts. In short, physical expansion opportunities are very limited and increasingly unpopular as means of solving the problem of urban congestion. More effective system management, including pricing strategies and investments in other modes, will be needed.

- ***Ensuring that the system remains responsive to, and aligned with, continued changes in the geography and composition of the country's population and economy, and that its connections with the other modes of local, interregional, and long-distance passenger and freight transportation are maintained and strengthened.*** Although thousands of miles of high-quality highways other than Interstates connect many of the country's population centers, lack of access to the Interstate System may be viewed by some smaller communities and emerging cities as detrimental to their growth and development, particularly given that the Interstate System includes the country's main trucking corridors and connects to many of the country's largest ports and rail hubs. The Interstate System was planned in the 1950s and considered complete in the 1990s, despite a changing economy and pattern of demand that is increasingly urban, western, and southern.
- ***Continually improving the system's safety as traffic volumes increase, new highway and vehicle technologies are introduced, and the system is modified to increase capacity and throughput.*** Although the Interstates are the nation's safest highways, they account for more than 5,000 traffic deaths annually. It will be important for the Interstates of the future to continue to adopt state-of-the-art safety practices that mitigate the additional risks arising from growth in traffic volume, and to ensure that efforts to increase traffic flow are accompanied by measures that counter adverse safety effects.
- ***Ensuring that the system is robust and adaptable to changing vehicle technologies, and avoiding premature investments in assets and the introduction of standards that would hinder or even foreclose useful development pathways.*** Many new technologies being developed, and in some cases introduced, have the potential to alter the operation and safety performance of the highway system, including the Interstates. Many of these technologies, such as driving assist features and automated vehicles, are vehicle-centered, while others, such as real-time traffic analysis systems that inform traffic control devices, have a strong infrastructure orientation. Other technologies will involve the connectivity of vehicles and infrastructure. The potential implications of the development and deployment of connected and automated vehicle technology for the future of the Interstate Highway System is a complex topic, involving many potential technologies, systems, and capabilities.
- ***Adopting funding mechanisms that are equitable and efficient, do not unduly impose the burden of payment on future generations or on less financially equipped groups, and do not disadvantage or***

divert resources from other highways and modes of passenger and freight transportation. The Interstate highway program has long been funded by user fees that have both efficiency and equity merits. However, user fee receipts have been stagnant, failing to keep pace with inflation and growth in motor vehicle travel in recent years. Part of the reason for this circumstance is that the federal fuel tax has not been increased in one-quarter of a century. Increasing vehicle fuel efficiency and the growing use of electric vehicles risk further revenue declines. Without new funding mechanisms, the longstanding federal contribution to the Interstate System may wane.

- ***Developing and implementing strategies for incorporating future climate conditions into infrastructure and operations planning, starting with the development of robust design and construction standards that accommodate greater frequency and severity of extreme weather events.*** When much of the Interstate System was being planned, designed, and built during the 1950s, 1960s, and 1970s, there was no recognition of the threat of the buildup greenhouse gases and of how a changing climate could adversely affect the transportation system and other critical infrastructure through such consequences as rising sea levels and extreme weather events. It is now certain, however, that transportation agencies across the country will need to make changes in the planning, design, construction, operation, and maintenance of their highways to account for these impacts.

AN INVESTMENT IMPERATIVE

The ability of states, metropolitan planning organizations (MPOs), and the federal government to collaborate and make informed choices about how much, when, and where investments in the Interstate Highway System should be made, as well as to monitor and evaluate system conditions and performance, is currently hindered by a paucity of data and decision-making tools. These inadequacies, particularly as they pertain to the system's structural condition and network-level functionality, impeded the committee's efforts to assess the physical state and operational performance of the system, much less to consider how its condition and performance are likely to change over the next several decades. Even in the face of this lack of data and decision-making tools, however, the inadequacies of the nation's prevailing reinvestment in the system are glaring.

Most of the Interstate Highway System has far exceeded its design life or will do so over the next 20 years. Only limited planning and budgetary preparations have been made to fix the deterioration that has already been incurred and to prevent the physical and operational deficiencies that will ensue. Recent combined state and federal capital spending on the Interstates has been on the order of $20–$25 billion annually (see Table 7-1). The information gathering, modeling, and case studies that informed this study indicate that this level of spending is too low—by at least 50 percent—just to proceed with the long-deferred rebuilding of the system's aging and deteriorating pavements and bridges. The committee estimates that investments averaging more than $30 billion per year will be needed over the next 20 years to repair and reconstruct these assets from damage already done and that is forthcoming from the effects of age and further use (see Table 7-1).

Along with these substantial investments in pavement and bridge repair and reconstruction, additional investments will be required to expand and manage the Interstate Highway System's capacity to handle future traffic. While the need for pavement and bridge upgrades can be estimated with a fair amount of confidence because of the predictable physical effects of age and wear, the investments that will be required to accommodate traffic demand are much more difficult to project. Capacity investments will likely be required, but their size, location, and timing will depend on a host of factors related to changes in the population and economy, how travelers respond to congestion and the supply of new capacity, and the availability of options other than Interstate travel. Transportation agencies, especially in urban areas, may substitute more active operations and demand management measures, such as congestion tolling, for spending on lane widening

TABLE 7-1 Estimated Spending Needs for Interstate Highway Renewal and Modernization Over the Next 20 Years

	2014 State and Federal Investment ($ billions)	Average Annual Investment ($ billions) Annual Growth in Vehicle-Miles Traveled (VMT)		
		Modest	Nominal	High
		0.75%	1.5%	2%
Resurfacing, partial and full reconstruction	$16	$27	$29	$32
Bridge rehabilitation and replacement	$4	$4	$4	$4
Capacity increase	$1	$13	$22	$31
Operations	$0.4	$2	$2	$2
TOTAL	$21.4	$46	$57	$69

NOTES: All dollar figures are converted 2016 values. The most recent complete data on interstate highways spending is for 2014. See Chapter 5 for details on computation methods.

and other physical additions to Interstate highways. Although connected and automated vehicles are likely to have limited effects on travel demand in the nearer term, expectations about their longer-term impact may influence transportation agency decisions about whether and where to invest in Interstate capacity, especially in 10 to 15 years.

The results of modeling and other analytic tools offer little insight into Interstate highway capacity needs 50 years out but are also questionable for a 20-year period because of the many uncertainties and interdependencies noted above. By stretching the limited modeling capabilities that do exist and using a range of historically informed rates of growth in future Interstate travel, the committee could, at best, make rough approximations of the magnitude of spending that will be needed for physical and operational capacity improvements over the next 20 years. The models calculate that if travel on the system is assumed to grow at a modest pace comparable to the forecast U.S. population (0.75 percent growth annually), transportation agencies will need to invest an average of $15 billion per year for such improvements. These investments would need to be considerably larger, by about 50 to 100 percent, if travel on the system is assumed to grow at a pace closer to recent historical averages (see Table 7-1).

Thus, an approximation of the total state and federal spending that will be needed to renew and modernize the Interstates over the next 20 years averages $45–$70 billion per year. The figures in this range are two to three times higher than current spending levels, and even 50 percent higher when only considering the outlays that will be required for the pavement and bridge upgrades that can be projected with higher confidence. However, even these estimated investment levels may be inadequate.

This estimated annual investment omits the spending that will be required in four areas that cannot be estimated at this time but are certain to require billions, and perhaps many billions, in additional spending. The following are examples of these investments:

- ***Reconfiguring and reconstructing many of the system's roughly 15,000 interchanges.*** The current condition of Interstate interchanges is not recorded in the national database on Interstate assets, and their improvement needs cannot be assessed using existing modeling tools.
- ***Making the system more resilient to the effects of climate change.*** These costs are likely to be highly dependent on local context and have not yet been adequately investigated.
- ***Expanding and allocating system capacity more efficiently in and around metropolitan areas.*** While the committee was able to derive estimates of the spending that would be required to pursue some congestion mitigation options, such as adding new general-purpose

and managed lanes, many urban Interstate segments will require the use of a wider array of technological, operational, and other demand-management approaches—such as intermodal connectivity strategies, area-wide congestion pricing, and the building of new transportation facilities—to accommodate future growth in travel demand. The investment required to pursue all of these congestion-management approaches could not be estimated.

- ***"Rightsizing" the length or scope of the system through extensions and replacements of some controversial urban segments that do not serve through-traffic.*** Estimation of the cost of such investments is plagued by uncertainty regarding how future demographic, economic, and technological developments will affect specific locations of growth in population and commerce; the lack of compelling criteria for justifying federal investment in such segments; and variation in the choices communities will make regarding the intrusiveness and environmental consequences of potential system modifications.

The scale and scope of the Interstate reinvestment imperative is daunting, but even more so in an environment in which the revenues needed to pay for the needed investments are flat or falling, as is the case for funds derived from system users. In the committee's view, that situation must change. Having motorists pay for the highway system they use not only is intrinsically fair but also provides opportunities to manage demand and allocate capacity through pricing, while also offering greater assurance that the revenues generated for reinvestment will not be outpaced by the demands placed by users of the system. It is with these expectations and opportunities in mind, together with recognition of the large and inevitable investment requirements lying ahead, that the committee offers the following recommendations. The original Interstate Highway System Construction Program was underpinned by a long-term, collaborative commitment among the states and the federal government. A comparable commitment will be needed to modernize the system and ensure that it is responsive and resilient to changing demands and well integrated with broader passenger and freight transportation systems. The federal government remains best positioned to ensure that each state's Interstate investments contribute to a well-functioning, nationally and regionally integrated highway network. This can be accomplished by ensuring that routes critical to connectivity are provided and maintained, even in cases in which they are perceived to have limited local- or state-level benefit. For their part, states—in cooperation with their metropolitan planning organizations and local governments—remain well suited to developing common standards and carrying out their traditional responsibilities in the allocation of resources for Interstate highway construction, operations, and maintenance.

RECOMMENDATIONS

Because the renewal and modernization of the Interstate Highway System will require large and sustained investment, federal leadership will be essential, along with funding that is both sufficient and reliable. The committee's recommendations are offered with these aims and outcomes in mind.

Recommendation 1. Congress should legislate an Interstate Highway System Renewal and Modernization Program (RAMP). This program, presumed to be pursued without sacrificing normal ongoing system maintenance and repair, should focus on reconstructing deteriorated pavements, including their foundations, and bridge infrastructure; adding physical capacity and traffic demand and operations management capabilities (e.g., tolling) where needed; and increasing the system's resilience. RAMP should be modeled after the original Interstate Highway System Construction Program by

- Reinforcing the traditional program partnership in which the federal government provides leadership in establishing the national vision for the overall system, the bulk of the needed funding, and overall standards, while states prioritize and execute projects in their continued role as owners, builders, operators, and maintainers of the system;
- Ensuring that the federal share of project spending is comparable to the 90 percent share of the original Interstate Highway System Construction Program;
- Committing the federal government to supporting projects from start to finish, but with a cap on total federal funding (i.e., a cost-to-complete approach); and
- Developing transition plans for updating and incorporating standards for system uniformity and safety to accommodate changing vehicle and highway technologies, environmental and climate conditions, and usage patterns.

Recommendation 2. A "rightsizing" component of RAMP should address current and emerging demands to extend the Interstate System's length and scope of coverage, and to remediate economic, social, and environmental disruption caused by highway segments that communities find overly intrusive and are not deemed vital to network and intermodal traffic. Congress should direct the U.S. Department of Transportation (U.S. DOT) and the Federal Highway Administration (FHWA) to develop criteria for such system rightsizing using a consultative process that involves states, local jurisdictions, highway users, and the general public. The criteria and their development should take into account the interest in ensuring

- Adequate system connectivity and significant network flows of Interstate travel and commerce, including traffic from other important passenger and freight transportation modes;
- System access to growing centers of population and economic activity;
- System resilience through redundancy or other means as appropriate; and
- Responsiveness to national defense needs.

Recommendation 3. To better ascertain the spending levels required for RAMP investments, Congress should direct U.S. DOT and FHWA to join with the states to assess the foundational integrity of the system's pavements and bridges, and identify where full reconstruction is needed based on accepted life-cycle cost principles.

Recommendation 4. To pay for RAMP investments, Congress should, as a near-term step, (1) increase the federal motor fuel tax to a level commensurate with the federal share of the required investment, and (2) adjust the tax as needed to account for inflation and changes in vehicle fuel economy.

Recommendation 5. To provide states and metropolitan areas with more options for raising revenue for their share of RAMP investments and for managing the operations of Interstate segments that offer limited opportunity for physical expansion, Congress should lift the ban on tolling of existing general-purpose Interstate highways. As a condition for imposing those tolls, states should be required to assess their impact on current users and offer alternative mobility options for those users significantly and disproportionately harmed by the tolls.

Recommendation 6. To ensure that the federal government's long-term commitment to RAMP is not threatened by declining fuel tax revenues as the vehicle fleet and its energy sources evolve, Congress should prepare for the need to employ new federal and state funding mechanisms, such as the imposition of tolls or per-mile charges on users of the Interstate Highway System.

Recommendation 7. To support renewal and modernization investment decisions, Congress should direct, and provide sufficient funding for, U.S. DOT and FHWA to develop modeling tools and databases that

- Track the full condition of Interstate assets, including interchanges, and their reconstruction history;
- Can be used to assess transportation options that can supplement or substitute for additions to Interstate highway capacity;
- Allow for the monitoring and modeling of network-level traffic flows on the Interstate Highway System; and
- Further federal and state understanding of the demand for long-distance and interregional passenger and freight travel by highway and other modes.

Because these recommended activities are important for guiding reinvestment in the Interstate System, careful consideration should be given to carrying them out in an effective and efficient manner.

Recommendation 8. Congress should direct U.S. DOT and FHWA, working with states, industry, and independent technical experts, to start planning for the transition to more automated and connected vehicle operations. This effort should entail the needed research and updates to Interstate Highway System requirements and standards so as to ensure that basic intelligent transportation system (ITS) instrumentation is adopted on a consistent and system-wide basis, and that the uniformity and other attributes of pavement markings, interchange design, and the like are capable of facilitating eventual Interstate use by connected and automated vehicles.

Emphasis should be placed on ensuring that renewal and modernization projects give full consideration to safety impacts, including the deployment of advanced design and operational features that have demonstrated effectiveness in improving safety; and that cybersecurity protections are incorporated into the designs and upgrades of the Interstate highways and the vehicles that use them.

Recommendation 9. Expanding on earlier legislative directives (e.g., the Moving Ahead for Progress in the 21st Century [MAP-21] Act and the Fixing America's Surface Transportation [FAST] Act) for transportation agencies to consider resilience in long-term planning, Congress should direct U.S. DOT and FHWA to substantiate that state Interstate highway renewal and modernization projects have fully taken into account the need for resilience. To support these efforts, U.S. DOT and FHWA should be directed to

- Assess the vulnerability of the Interstate Highway System to the effects of climate change and extreme weather;
- Develop standards, in conjunction with states, for incorporating cost-effective resilience enhancements into projects; and

- Develop and maintain a database of cost-effective practices and resilience strategies employed by state highway and other transportation agencies, including any funding mechanisms dedicated to support resilience planning and implementation.

Recommendation 10. Congress should direct U.S. DOT and FHWA to ascertain the Interstate Highway System's contribution to the country's emission of greenhouse gases and other pollutants and recommend options for reducing this contribution in conjunction with reduction in other emissions of pollutants, requiring states to consider the emissions impacts of capacity expansion and demand-management options, and legislation mandating a federal program to examine the siting of facilities that support alternative-fueled vehicles, such as electric vehicle charging stations located on Interstate highway corridors.

CONCLUDING COMMENTS

Central to the blueprint for action detailed in this chapter is federal leadership, starting with the resolve to reestablish the Interstate Highway System's premier status and to ensure that this status is no longer allowed to obsolesce. Implementation of the committee's recommendations would require a fundamental shift away from federal policy that has lost focus on the Interstate System and the commitment to funding it adequately. The recommended actions would restore the system's premier status within the national highway program in a manner that is aggressive and ambitious, but by no means novel. Taking these actions would rekindle a tried-and-true federal–state partnership; reinforce the system's long-standing reliance on user fees to provide a fair, adequate, and reliable source of funding; and reassert the forward-looking vision that was instrumental to the genesis of this crucial national asset more than a half-century ago.

Appendix A

Study Committee Biographical Information

Norman R. Augustine (NAS, NAE), *Chair*, is the retired chairman and CEO of Lockheed Martin Corporation. In 1958 he joined the Douglas Aircraft Company in California, where he worked as a Research Engineer, Program Manager, and Chief Engineer. Beginning in 1965, he served in the Office of the Secretary of Defense as Assistant Director of Defense Research and Engineering. He joined LTV Missiles and Space Company in 1970, serving as Vice President, Advanced Programs and Marketing. In 1973, he returned to the government as Assistant Secretary of the Army and in 1975 became Under Secretary of the Army, and later Acting Secretary of the Army. Joining Martin Marietta Corporation in 1977 as Vice President of Technical Operations, he was elected CEO in 1987 and Chairman in 1988, having previously been President and COO. He served as President of Lockheed Martin Corporation upon the formation of that company in 1995, and became CEO later that year. He retired from Lockheed Martin in August 1997, at which time he became a Lecturer with the rank of Professor on the faculty of Princeton University, where he served until July 1999. Since retiring he has chaired or co-chaired 32 pro bono commissions or committees, mostly for various levels of government.

Mr. Augustine was Chairman and Principal Officer of the American Red Cross for 9 years, Chairman of the Council of the National Academy of Engineering, President and Chairman of the Association of the U.S. Army, Chairman of the Aerospace Industries Association, and Chairman of the Defense Science Board. He is a former President of the American Institute of Aeronautics and Astronautics and the Boy Scouts of America. He is a former member of the Board of Directors of ConocoPhillips, Black

& Decker, Proctor & Gamble, and Lockheed Martin, and was a member of the Board of Trustees of Colonial Williamsburg. He served for 10 years as Regent of the University System of Maryland, Trustee Emeritus of Johns Hopkins, and a former member of the Board of Trustees of Princeton and MIT. He served for 16 years on the President's Council of Advisors on Science and Technology and is a member of the American Philosophical Society, the National Academy of Sciences, the National Academy of Engineering, and the Council on Foreign Affairs, and is a Fellow of the American Academy of Arts and Sciences and the Explorers Club. Mr. Augustine has been presented the National Medal of Technology by the President of the United States and received the Joint Chiefs of Staff Distinguished Public Service Award. He has five times received the U.S. Department of Defense's highest civilian decoration, the Distinguished Service Medal. He is co-author of *The Defense Revolution* and *Shakespeare in Charge* and author of *Augustine's Laws*, *Augustine's Travels,* and "The Way I See It." He holds honorary degrees from 35 universities and was selected by Who's Who in America and the Library of Congress as one of "Fifty Great Americans" on the occasion of Who's Who's 50th anniversary. He holds a B.S.E. and an M.S.E. in aeronautical engineering from Princeton University.

Vicki Arroyo is the founding Executive Director of the Georgetown Climate Center at Georgetown Law, where she also serves as the Assistant Dean of Centers and Institutes and a Professor from practice. Georgetown Climate Center was launched in 2009 to inform the federal dialogue with the lessons of leading states and to serve as a resource to states and cities on climate change mitigation and adaptation. Previously, Ms. Arroyo served for more than a decade at the Pew Center on Global Climate Change as Vice President for policy analysis and general counsel. She served as Managing Editor of the book, *Climate Change: Science, Strategies, and Solutions*. In addition to teaching at Georgetown, Ms. Arroyo has taught courses on environmental policy and climate change at Catholic University, George Mason University's graduate public policy program, and Tulane Law School. She practiced environmental law with Kilpatrick Stockton and other private firms and served in two offices at the U.S. Environmental Protection Agency: the Office of Air and Radiation and the Office of Research and Development, where she reviewed development of standards under the Clean Air Act. From 1988 to 1991, Ms. Arroyo created and directed the Louisiana Department of Environmental Quality's policy office, and served during some of that time as the governor's environmental advisor. She has served on several federal panels, including those reviewing economic modeling of climate legislation for the U.S. Department of Energy's Energy Information Administration, on the National Science Foundation's advisory committee to the geosciences directorate, and on a federal study informing climate change adaptation along the Gulf Coast. She also served on an advisory committee to California Air Resources Board on its cap-and-trade program design, and on the Board of Trustees for the University Corporation for Atmospheric Research, which oversees the National Center for Atmospheric Research. Ms. Arroyo currently serves as Vice Chair of the Transportation Research Board (TRB) of the National Academies of Sciences, as committee member on a TRB study initiated by Congress that is exploring the future of the interstate highway system, and as Chair of TRB executive committee's resilience and sustainability task force. She is an Associate Editor of the *Climate Policy* journal and publishes widely on climate, energy, and transportation issues. She earned a bachelor's in science with high honors from Emory University (biology, double major in philosophy), a master's in public administration from Harvard (Don K. Price award for academic achievement and commitment to public service), and a juris doctorate magna cum laude from Georgetown University Law Center, where she served as Editor-in-Chief of the Georgetown International Environmental Law Review. Ms. Arroyo was named one of PODER Hispanic Magazine's Green 100, featured in its Earth Day issue (April 2013) and as one of Glamour Magazine's Top Ten College Women (1985). Her TED Global Talk on preparing communities for climate change impacts has been viewed more than 1 million times.

Moshe Ben-Akiva is the Edmund K. Turner Professor of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT), and Director of the MIT Intelligent Transportation Systems (ITS) Lab. His awards include the Lifetime Achievement Award of the International Association for Travel Behavior Research, the Jules Dupuit prize from the World Conference on Transport Research Society (WCTRS), and the Institute of Electrical and Electronics Engineers (IEEE) ITS Society Outstanding Application Award for DynaMIT, a mesoscopic simulator with algorithms for dynamic traffic assignment, traffic predictions, and travel information and guidance. Dr. Ben-Akiva has co-authored two books, including the textbook *Discrete Choice Analysis*, published by MIT Press, and more than 200 papers in refereed journals or conference proceedings. He has been a member of more than three dozen various scientific committees, advisory boards, and editorial boards. He has worked as a consultant in industries such as transportation, energy, telecommunications, financial services, and marketing for a number of private and public organizations. He holds a Ph.D. and an M.S. in transportation systems from the Massachusetts Institute of Technology and a B.S. from Technion-Israel Institute of Technology, along with honorary degrees from the University of the Aegean, the Université Lumiére Lyon, the Royal Institute of Technology (KTH), and the University of Antwerp.

Ann Drake is the Chairman and former Chief Executive Officer of DSC Logistics. She has guided DSC to become one of the leading supply chain management firms in the United States by creating a business model based on integrated, comprehensive supply chain solutions built on collaborative partnerships, innovative thinking, and high-performance operations. Ms. Drake is a member of the Kellogg School Global Advisory Board at Northwestern University, serves on the Board of Governors for Chicago's Metropolitan Planning Council, and is a member of the Board of Trustees for Chicago's Museum of Science and Industry. She was appointed to the Committee on Future Interstate Highway System by the National Academies of Sciences, Engineering, and Medicine, and is a member of the Civic Committee Transportation Task Force. She has served as a member of the Board of Directors for the A.M. Castle Company and the Board of Governors for the Committee of 200, and as Vice Chair of the Business Advisory Council for the Northwestern University Transportation Center. In 2013, Ms. Drake founded AWESOME (Achieving Women's Excellence in Supply Chain Operations, Management, and Education), a network that has grown to include more than 1,000 women in a range of senior-level supply chain roles. She is a charter member of Paradigm for Parity, a coalition of business leaders working for gender parity by the year 2030. Ms. Drake received the 2015 Schultz Award for advancing women in transportation and logistics from the McCormick School of Northwestern University. She was honored with the global "Women Who Make a Difference" Award from International Women's Forum (IWF) in 2014. In 2012 she received the Council of Supply Chain Management Professionals (CSCMP) Distinguished Service Award and the Alumni Merit Award from the Kellogg School of Management of Northwestern University; in 2009 she was named "Industry Leader of the Year" by Illinois Institute of Technology. Ms. Drake received an undergraduate degree from the University of Iowa and an M.B.A. from the Kellogg School of Management of Northwestern University.

Genevieve Giuliano holds the Margaret and John Ferraro Chair in Effective Local Government in the Sol Price School of Public Policy, University of Southern California (USC), and is Director of the METRANS, a joint USC and California State University Long Beach Transportation Center. Her research areas include relationships between land use and transportation, transportation policy analysis, travel behavior, and information technology applications in transportation. Current research includes examination of relationships between land use and freight flows, spatial analysis of freight activity location, impacts of freight activities on local communities, impacts of rail transit investments on transit ridership and economic development, and applications for transportation system analysis using archived real-time data. She has published more than 170 papers. Professor Giuliano is a past Chair of the Executive Committee of the Transportation Research Board, and of the Council of University Transportation Centers. She has received numerous distinguished scholarship and service awards. She is a member of several advisory boards, including the National Freight Advisory Committee.

Steve Heminger is Executive Director of the Metropolitan Transportation Commission (MTC). MTC is the regional transportation planning and finance agency for the nine-county San Francisco Bay Area. It allocates more than $2 billion per year in funding for the operation, maintenance, and expansion of the Bay Area's surface transportation network. Under contract with the Association of Bay Area Governments, Mr. Heminger and his team also provide staffing and support services to that organization. Since 1998, MTC has served as the Bay Area Toll Authority (BATA) responsible for administering all toll revenue from the seven state-owned bridges. BATA has an "AA" credit rating and has issued more than $9 billion in toll revenue bonds to finance bridge, highway, and transit construction projects over the next several years. MTC also functions as the region's Service Authority for Freeways and Expressways (SAFE), operating a fleet of Freeway Service Patrol tow trucks and a network of roadside call boxes to assist motorists in trouble. In addition, MTC manages the FasTrak electronic toll-collection system, the Clipper universal fare card program for public transit and the popular 511 traveler information telephone number and website. Mr. Heminger was appointed by House Democratic Leader Nancy Pelosi to serve on the National Surface Transportation Policy and Revenue Study Commission, which helped chart the future course for the federal transportation program. As Chairman of the Toll Bridge Program Oversight Committee, Mr. Heminger also oversaw construction of the new East Span of the San Francisco–Oakland Bay Bridge—the largest transportation project in California history. In addition, he is a member of the Board of Trustees for the Mineta Transportation Institute and a member of the Executive Committee for the Transportation Research Board. Mr. Heminger holds an M.A. from the University of Chicago and a B.A. from Georgetown University.

Chris Hendrickson (NAE) is the Hamerschlag University Professor of Engineering Emeritus, Director of the Traffic 21 Institute at Carnegie Mellon University, member of the National Academy of Engineering, and Editor-in-Chief of the American Society of Civil Engineers (ASCE) *Journal of Transportation Engineering*. His research, teaching, and consulting are in the general area of engineering planning and management, including design for the environment, project management, transportation systems, finance, and computer applications. He has co-authored four textbooks all available for free on the Internet: *Fundamentals of Infrastructure Management* (2017), *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter* (2014), *Project Management for Construction* (Prentice-Hall, 1989, now available on the Web), and *Civil Systems Planning, Investment and Pricing* (2011). He has also published several monographs and numerous papers in the professional and public literature. Professor Hendrickson is a member of the National Academy of Engineering, the National Academy of Construction, a Distinguished Member of the American Society of Civil Engineering, an Emeritus Member of the Transportation Research Board, and a Fellow of the American Association for the Advancement of Science. He has been the recipient of the 2002 ASCE Turner Lecture Award, the 2002 Fenves Systems Research Award, the 1994 Frank M. Masters Transportation Engineering Award, Outstanding Professor of the Year Award of the ASCE Pittsburgh Section (1990), the ASCE Walter L. Huber Civil Engineering Research Award (1989), the Benjamin Richard Teare Teaching Award (1987), and a Rhodes Scholarship (1973).

Keith Killough is an Urban Planning graduate of the Massachusetts Institute of Technology and holds professional certification from the American Institute of Certified Planners. Early in his career, he assisted the (Boston) South End Project Area Committee in community transportation planning and worked in the Office of Municipal Planning & Management for the Massachusetts Department of Community Affairs, where he developed municipal master plans under the HUD 701 Program. He then joined Barton-Aschman Associates in Washington, D.C., where he focused on regional transportation planning, transportation systems management, transit development, bikeway planning, traffic engineering, and parking analysis studies. One of his projects, the "District of Columbia Bicycle Transportation Plan and Program," received two awards: The American Institute of Planners National Capitol Area Chapter "Outstanding Transportation Planning Award"; and, the Urban Bikeway Design Collaborative's "First Place—Professional Design Award." Mr. Killough next worked for the Southeast Michigan Council of Governments responsible for the Regional Transportation Plan, a new travel forecasting model, and a regional household travel survey. In his next position with the Southern California Rapid Transit District, Mr. Killough served as Planning Manager and was responsible for ridership forecasting and background bus coordination planning for the Metro Red Line subway, transit surveys and analyses, FTA Section 15 and Title VI submittals, management performance indicator reporting, transportation system service and fare options analyses, rail and facilities elements of the Short Range Transit Plan, and the implementation of computerized planning information systems. In 1993, he became Deputy Executive Officer at the Los Angeles County Metropolitan Transportation Authority (MTA). His responsibilities included countywide strategic planning and administration of Transit Planning, the Congestion Management Program, the Americans with Disabilities Act transportation services, Ridesharing Services, Market Research, Travel Simulation and Geographic Information System Analyses, and the Library/Information Center. He was a key contributor to numerous innovative transportation policies and programs such as Metro Rapid Bus. He was the principal coordinator for the 1995 MTA Long-Range Transportation Plan.

In 2001, he formed KLK Consulting specializing in transportation planning and analysis for various agencies including: the California Department of Transportation, the Southern California Association of Governments, the Los Angeles Department of Transportation, and the San Diego Association of Governments, and expert review panels in both the United States and Canada. In 2005, he became Director of Information Services with the Southern California Association of Governments responsible for travel simulation modeling, information technology, data and monitoring, and office management. He is currently Director of Transportation Analysis in the Multimodal Planning Division of the Arizona Department of Transportation with responsibilities including travel demand modeling, statewide traffic monitoring, and the federally required Highway Performance Monitoring System. He represented the transit industry on the federal Travel Model Improvement Program that provided oversight to the TRANSIMS model development project. Additionally, he has participated on numerous expert panels for various state and regional agencies, the Federal Highway Administration, and the Transportation Research Board (TRB), including TRB Policy Study Committee for the Interregional Travel Study, TRB Standing Committees for Transportation Demand Forecasting and Transportation Planning Applications, and National Cooperative Highway Research Program (NCHRP) committees for NCHRP 08-36: Research for the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Planning, and panel chair for the NCHRP 0894: Guidelines for Selecting Travel Forecasting Methods and Techniques and NCHRP 08-110: Traffic Forecasting Accuracy Assessment Research.

Adrian Lund is currently a consultant and a managing member at HITCH42, LLC. The mission of HITCH42 is to provide individuals and society with empirical knowledge to make better and safer decisions. Dr. Lund recently retired from the Insurance Institute for Highway Safety (IIHS) and its affiliate, the Highway Loss Data Institute (HLDI), where he had served for 36 years, most recently as President from 2006 through 2017. His research there spanned the range of driver, vehicle, and roadway factors involved in motor vehicle safety. As Senior Vice President for Research at IIHS from 1993 to 2001, he directed the development of the Institute's vehicle crashworthiness testing program at its (then) state-of-the-art Vehicle Research Center. As President, he oversaw the expansion of the Institute's Vehicle Research Center to include new facilities, and the world's first fully covered outdoor vehicle test track, for evaluating and promoting new technology that promises to help drivers avoid crashes and, eventually, to operate vehicles safely without drivers. Dr. Lund is a recognized media authority on highway safety and was included in Motor Trend's Power List in 2015 and 2016. Before joining IIHS, Dr. Lund was an Assistant Professor in residence at the University of Connecticut Health Center (1975–1981), where he studied people's health behavior. Currently, he serves as a Trustee for the Global New Car Assessment Programme; as a member of the University of Michigan's International Center for Automotive Medicine (ICAM) advisory board; as a member of the National Safety Council's Road to Zero Coalition; as a member of Autoliv's Research Advisory Board; and as a member of the National Academy of Sciences Committee on the Future of the Interstate Highway System.

Dr. Lund received a B.A. in psychology from North Carolina State University, and his M.A. and Ph.D. in social psychology from the State University of New York at Buffalo. He is a member of the Society of Automotive Engineers, American Public Health Association, and American Psychological Association.

Joan McDonald is the Principal of JMM Strategic Solutions and a member of the National Infrastructure Advisory Council. Ms. McDonald is former Commissioner of the New York State Department of Transportation and former Commissioner of the Connecticut Department of Economic and Community Development. From February 2011 until July 2015, she served as the 11th Commissioner of the New York State Department of Transportation, an organization with 8,300 employees and an annual budget of $4 billion. Ms. McDonald led the department through various weather events (Hurricane Irene, Superstorm Sandy, and the 2014 Buffalo "Snovember to Remember"). As Commissioner, Ms. McDonald chaired the Northeast Corridor Commission, co-chaired the Tappan Zee Bridge Mass Transit Task Force, and served on the Executive Committee of the Transportation Research Board. As Commissioner of the Connecticut Department of Economic and Community Development from June 2007 through January 2011, Ms. McDonald led Connecticut's economic development efforts through the "Great Recession." Under her leadership, the state developed its first ever strategic economic development plan, negotiated agreements with several Fortune 500 companies, and initiated transit oriented development in all of Connecticut's major cities. Ms. McDonald also served in senior management positions for the City of New York, where she negotiated the 50-year lease with the Port Authority of NY/NJ for Kennedy and LaGuardia

Airports; lead the transfer and re-alignment of traffic enforcement agents from NYCDOT to NYPD; and oversaw environmental reviews of the Harlem Line Third Track and the Hudson River Park. In the private sector, Ms. McDonald led the efforts of Jacobs Engineering in New York and New Jersey. She holds an M.S. in public administration from Harvard University.

Norman Mineta is President and Chief Executive Officer of Mineta & Associates, LLC. He is well known for his work in transportation—including aviation, surface transportation, and infrastructure—and national security. He is recognized for his accomplishments in economic development, science and technology policy, foreign and domestic trade, budgetary issues, and civil rights, as well as his perspective from having served in Congress for more than 20 years and in the Cabinets of both Republican and Democratic presidents. For almost 30 years, Secretary Mineta represented San Jose, California, first on the City Council, then as Mayor, and then from 1975 to 1995 as a member of Congress. Throughout that time, Secretary Mineta was an advocate of the burgeoning technology industry. He worked to encourage new industries and spur job growth, and he supported infrastructure development to accommodate the industry and its tremendous growth. Secretary Mineta served as the Chairman of the House Transportation and Public Works Committee from 1992 to 1994, after having chaired the Subcommittee on Aviation and the Subcommittee on Surface Transportation. He was the primary author of the groundbreaking ISTEA legislation—the Intermodal Surface Transportation Efficiency Act of 1991. While in Congress, he co-founded the Congressional Asian Pacific American Caucus and was Chair of the National Civil Aviation Review Commission in 1997. In 2000, Secretary Mineta was appointed by President Bill Clinton as the U.S. Secretary of Commerce. At the U.S. Department of Commerce, Secretary Mineta was known for his work on technology issues, for achieving international cooperation and intergovernmental coordination on complex fisheries issues, and streamlining the patent and trademark processes. From 2001 to 2006, Secretary Mineta served as Secretary of Transportation by President George W. Bush. Following the terrorist acts of September 11, 2001, Secretary Mineta guided the creation of the Transportation Security Administration—an agency with more than 65,000 employees—the largest mobilization of a new federal agency since World War II. Most recently and prior to establishing Mineta & Associates, Secretary Mineta served as Vice Chairman of Hill & Knowlton. Recognized for his leadership, Secretary Mineta has received numerous awards, including the Presidential Medal of Freedom—our nation's highest civilian honor—and the Wright Brothers Memorial Trophy, which is awarded for significant public service of enduring value to aviation in the United States. He holds a B.A. in business administration from the University of California, Berkeley.

Kirk T. Steudle is the Senior Vice President of Econolite. Prior to joining Econolite, Mr. Steudle was the Director of the Michigan Department of Transportation (MDOT) since 2006, where he oversaw MDOT's more than $4 billion budget, and was responsible for the construction, maintenance, and operation of nearly 10,000 miles of state highways and more than 4,000 state highway bridges at a department with 2,500 employees. He also oversees administration of a variety of multimodal transportation programs and projects. Mr. Steudle is a national leader in the development of Connected and Automated Vehicle Technologies, and was the 2014–2015 Chair for the Intelligent Transportation Society of America (ITS America) Board of Directors. He also is a member of the Intelligent Transportation Systems (ITS) Program Advisory Committee to the U.S. Department of Transportation. Mr. Steudle is a past President of the American Association of State Highway and Transportation Officials (AASHTO) and chairs the Standing Committee on Highways. He was a 2014 member of the National Research Council for the National Academy of Sciences and the 2014 Chair of the Transportation Research Board (TRB) Executive Committee. He also chaired the second Strategic Highway Research Program Oversight Committee (SHRP 2) for TRB and was a member of numerous National Cooperative Highway Research Program (NCHRP) panels and committees on asset and performance management. Mr. Steudle is the recipient of the 2011 P.D. McLean Award from the Road Gang in Washington, D.C., for excellence in highway transportation. In 2015, he was named one of America's Top 25 Government Innovators by Government Technology. Mr. Steudle is a graduate of Lawrence Technological University, where he received a bachelor of science degree in construction engineering, serves on the College of Engineering Advisory Board and he was inducted into its Hall of Fame in 2012.

Michael S. Townes recently retired as Senior Vice President and National Transit Market Sector Leader at HNTB Corporation. Mr. Townes served as Chief Executive Officer and President of Hampton Roads Transit from 1999 to January 31, 2010. Mr. Townes serves as Legislative Chair for the Conference of Minority Transportation Officials (COMTO) and the Virginia Transit Association. Since 2007, he served as Chairman of the American Public Transportation Association. He served as an Executive Director of Transportation District Commission of Hampton Roads (Hampton Roads Transit) since October 1, 1999. Beginning March 1, 1998, he also served as the Interim Executive Director for the Tidewater Transportation District Commission in preparation for the merger of the two agencies. In November 1986, he joined the Peninsula Transportation District Commission (PENTRAN) as an Assistant to the Executive Director and served as its Acting Executive Director since 1988 and Executive

Director since July 1989. He serves as a member of Board of Regent at Eno Transportation Foundation. Mr. Townes also belongs to the Board of Directors for the Virginia High Speed Rail Development Committee. He has served as Chair of the Transportation Cooperative Research Project (TCRP) Oversight and Project Selection (TOPS) Committee. He served as Chair of APTA Executive Committee. He served as Chair of APTA Executive Committee. He served as Co-Chair of the APTA's Reauthorization Task Force, which was the committee that established the national transit position on the upcoming reauthorization. Mr. Townes served as Chairman of the Norman Mineta Transportation Institute Board of Trustees, APTA's Legislative Committee Chair, and Chairman of the Transportation Research Board (TRB) Executive Committee. He was also appointed to Virginia's Specialized Transportation Committee by Governor George Allen in 1996. In 2007, he was appointed by Virginia Governor Timothy Kaine to serve on the Governor's Commission on Climate Change. He is the recipient of several distinguished awards including the COMTO Executive of the Year Award, the Women in Transit Committee Achievement Award, and the Distinguished Public Service Award from the Conference of Minority Public Administrators. Mr. Townes holds a B.S. in political science and an M.A. in urban regional planning from Virginia Commonwealth University.

C. Michael Walton (NAE) is Professor of Civil Engineering and holds the Ernest H. Cockrell Centennial Chair in Engineering at The University of Texas at Austin (UT). In addition, he holds a joint academic appointment in the Lyndon B. Johnson School of Public Affairs. For more than 45 years he has pursued a career in transport systems engineering and policy analysis. Dr. Walton was elected as a member of the National Academy of Engineering in 1993. In other professional society leadership positions, he is a past Chair of the Transportation Research Board (TRB) Executive Committee, past Chair of the Board of the American Road and Transportation Builders Association (ARTBA), past President of the Board of Governors of the Transportation and Development Institute of the American Society of Civil Engineers (ASCE), a founding member and past Chair of the Board of Directors of the Intelligent Transportation Society (ITS) of America and a member of many other technical and professional organizations such as the Institute of Transportation Engineers. Dr. Walton was appointed by the U.S. Secretary of Transportation to serve on the National Freight Advisory Committee. He currently chairs the Advisory Council on Transportation Statistics in the Office of the Assistant Secretary for Research and Technology of the U.S. Department of Transportation. He has served on or chaired a number of national study panels including those mandated by Congress and others of the National Research Council. Dr. Walton has received numerous honors and awards. He was elected as a Distinguished Member of the ASCE and was selected as a member of the inaugural class of ITS America's ITS Hall of Fame. He received an Honorary Doctorate Degree from the Nagoya Institute of Technology and the Council of University Transportation Centers (CUTC) award for distinguished contribution to university transportation education and research. Other honors include the Outstanding Projects and Leaders (OPAL) Award from the American Society of Civil Engineers to recognize and honor lifetime excellence in furthering civil engineering education; named to "America's Top 100 Private Sector Transportation Design and Construction Professionals of the 20th Century" by the ARTBA. The George S. Bartlett Award in recognition for outstanding contributions to highway progress and is considered to be among the highest honors in the highway transportation profession. ASCE has honored him with several awards including Presidents' Award, the Francis C. Turner Lecture, the James Laurie Prize, the Harland Bartholomew Award, and the Frank M. Masters Transportation Engineering Award. The Transportation Research Board presented him with the Frank Turner Medal for Lifetime Achievement in Transportation, W.N. Carey, Jr., Distinguished Service Award; others include the Thomas B. Deen Distinguished Lectureship. ARTBA awarded him the S.S. Steinberg Award; ITE awarded him the Wilbur S. Smith Distinguished Transportation Educator Award and the Theodore M. Matson Memorial Award. He was inducted into the Texas Transportation Hall of Honor and recently inducted into the Transportation Development Hall of Fame of the American Road and Transportation Builders Association Foundation. Dr. Walton has contributed to numerous publications in the areas of ITS, freight transport, and transportation engineering, planning, policy, and economics, and he has delivered several hundred technical presentations. He has served as senior editor or contributing author for a variety of technical reference books and manuals and as a member of the editorial board for several international journals. Currently Dr. Walton has a research or consulting relationship with several international universities, several public and private firms, and serves as a member on several boards of directors of both public and privately held companies.

Appendix B

Panelists Who Presented Testimony to the Study Committee

September 6–7, 2016
National Academy of Sciences Building
2101 Constitution Avenue, Washington, DC

- Gregory Nadeau, Administrator 2015–2017, Federal Highway Administration (FHWA)
- Michael Trentacoste, Associate Administrator for Research, Development & Technology (RD&T), FHWA
- Frederick "Bud" Wright, Executive Director, American Association of State Highway and Transportation Officials (AASHTO)
- Susan Binder, Senior Associate, Cambridge Systematics, Inc.
- Ross Crichton, Team Leader, Office of Transportation Policy Studies, FHWA
- Hal Kassoff, Senior Adviser and Principal Professional Associate, WSP
- Brian Pallasch, Managing Director, Government Relations and Infrastructure Initiatives, American Society of Civil Engineers

December 19–20, 2016
National Academy of Sciences Building
2101 Constitution Avenue, Washington, DC

Demographics and Vehicle-Miles Traveled Projections Based on Economic Trends

- Rolf Pendall, Co-Director, Metropolitan and Communities Policy Center, Urban Institute
- Tianjia Tang, Chief, Travel Monitoring and Surveys Division, FHWA

Travel Demand and Behavior: Freight, Passenger, and Multimodal

- Chris Caplice, Executive Director, Massachusetts Institute of Technology (MIT) Center for Transportation Logistics, MIT
- Robert Costello, Chief Economist and Senior Vice President, American Trucking Association
- Darnell Grisby, Director of Policy Development and Research, American Public Transportation Association
- Patricia Mokhtarian, Professor of Civil Environmental Engineering, Georgia Institute of Technology

Environmental and Resilience Issues

- Michael Culp, Team Leader, Sustainable Transport and Climate Change, FHWA
- Debra Nelson, Strategic Policy Advisor, New York State Department of Transportation (DOT)
- Carol Lee Roalkvam, Policy Branch Manager—Environmental Service, Washington State DOT

Technology

- Carl Haas, Research Chair, Construction and Management of Sustainable Infrastructure, Waterloo University
- Leslie Jacobson, Vice President and Senior ITS Manager, WSP Parsons Brinckerhoff
- Cameron Kergaye, Director of Research, Utah DOT
- Peter Sweatman, Principal, CAVita

Funding and Financing

- Asha Weinstein Agrawal, Director, Mineta Transportation Institute, San José State University
- Pat Jones, Executive Director and CEO, International Bridge, Tunnel and Turnpike Association
- Barb Rohde, Executive Director, Mileage-Based User Fee Alliance

- Alex Schroeder, Senior Advisor for the Office of the Assistant Secretary for Research and Technology, U.S. DOT

Highway Economic Requirements System (HERS) and National Bridge Investment Analysis System (NBIAS)

- Chad Clancy, Engineer/Associate, Modjeski & Masters
- Richard Margiotta, Principal, Cambridge Systematics Inc./Future Interstate Consulting
- Alan Pisarski, Alan Pisarski Consulting

Science of Uncertainty and Long-Term Scenario Planning

- Patricia Hendren, Executive Director, I-95 Corridor Coalition
- Robert Lempert, Principal Researcher and Director, Fredrick S. Pardee Center, RAND Corporation
- Brian Watts, Senior Transportation Analyst, Florida DOT

February 23–24, 2017
San Francisco Metropolitan Transportation Commission Headquarters
San Francisco, CA

Regional Planning

- Carlos Braceras, Director, Utah DOT
- Scott Kubly, Director, Seattle DOT
- Todd Lang, Director of Transportation Planning, Baltimore Metropolitan Council
- Maura Twomey, Executive Director, Association of Monterey Bay Area Governments

Interstate Coalitions

- Margaret Bowes, Executive Director, I-70 Coalition
- Michael Kies, Director of Multimodal Planning, Arizona DOT
- Victor Lindenheim, Executive Director, Golden State Gateway Coalition
- Kevin Verre, Transportation Planner, Nevada DOT

Innovative Financing

- Gustavo Dallarda, Corridor Director, California DOT
- Vincent Graham, Chairman, South Carolina Transportation Infrastructure Bank
- Jim Madaffer, Commissioner, California Transportation Commission (Madaffer Enterprise)
- Belen Marcos, President, Cintra U.S.

March 27–28, 2017
The Confidante Miami Beach
Miami Beach, FL

Climate Change and Resilience

- Elizabeth Habic, Climate Change Program Manager, Maryland DOT—SHA
- Joseph Krolak, Team Leader, Hydraulic and Geotechnical Engineering, FHWA
- James Lambert, Systems and Information Engineering, Research Professor, University of Virginia
- Allison Yeh, Executive Planner and Sustainability Coordinator, Hillsborough County Metropolitan Planning Organization

Environmental Impacts and Sustainability Issues

- Drew Joyner, Human Environment Section Head, North Carolina DOT—Human Environmental Section
- Wayne Kober, Pennsylvania DOT (Retired)
- Xavier Pagan, State Environmental Process Administrator, Florida DOT
- Eric Sundquist, Managing Director, University of Wisconsin/COWS

Human Environment and Equity

- Colette Pichon Battle, Executive Director, U.S. Human Rights Network
- Thomas Hawkins, Policy and Planning Director, 1000 Friends of Florida
- Jacqueline Patterson, Director, Environmental and Climate Justice Program, NAACP

Toll-Financed Reconstruction and Modernization

- Robert Poole, Co-Founder and Director of Transportation Policy, Reasons Foundation

Public Transit and the Interstate Highway System

- Edward Regan, Senior Vice President, Tolling Projects Director, CDM Smith
- Brad Thoburn, Vice President of Long-Range Planning and System Development, Jacksonville Transportation Authority
- Joel Michael Volinski, Director, National Center for Transit Research for Urban Transportation Research, University of South Florida

Miami Beach Resilience Improvement Program

- Margarita Wells, Acting Director, Environment and Sustainability, Miami Beach Government

May 16–17, 2017
Southeast Michigan Transportation Operations Center (SEMTOC)
1060 West Fort Street, Detroit, MI

Bridge Reconstruction

- Adam Penzenstadler, Projects and Contracts Administration Engineer, Michigan DOT

Connected and Automated Vehicles: Industry Perspective

- Colm Boran, Manager, Autonomous Vehicle Systems Engineering, Ford Motor Company
- Vivek Vijaya Kumar, Senior Researcher, General Motors
- Jeffery Skvarce, Engineering Manager, Continental Automotive Systems, Inc.

20th Century Review of the Interstate Highway System

- Bruce Seely, Dean of the College of Sciences and Arts, Michigan Technological University

Connected and Automated Vehicles Technology: Summary of Commissioned Paper

- Steven Shladover, California PATH Program Manager, University of California, Berkeley

Automated and Autonomous Freight Vehicles

- Randy Cole, Executive Director, Ohio Turnpike and Infrastructure Commission
- William Panos, Director, Wyoming DOT
- Joshua Switkes, Founder and CEO, Peloton Technology Inc.

Automated and Autonomous Passenger Vehicles

- Hideki Hada, Executive Engineer, Active Safety, Toyota Motor Company
- Karl Heimer, Principal, Heimer & Associates, Founding Partner, AutoImmune Inc.
- Matthew Schwall, Director, Field Performance Engineering, Tesla Motors
- Dushyant Wadivkar, Advanced Engineering Manager, Robert Bosch LLC

Interstate System Operations and Management

- Michael Fontaine, Associate Principal Research Scientist, Virginia Transportation Research Council
- Sandra Larson, Research and Technology Bureau Director, Iowa DOT
- Sean Nozzari, Deputy District Director, California DOT

Asset Management and Preservation

- Laura Mester, Chief Administrative Officer, Michigan DOT
- Radney Simpson, Assistant State Transportation Planning Administrator, Georgia DOT

Demographic Projections—Today to 2060

- Guangqing Chi, Director, Computational and Spatial Analysis Core, The Pennsylvania State University

July 11–12, 2017
Metropolitan Planning Council, Marquette Building
140 S Dearborn Street, Chicago, IL

Travel Forecast

- Steven Polzin, Program Director, Mobility Policy Research, University of South Florida

Passenger Travel

- Kristina Boardman, Administrator, Division of Motor Vehicles, Wisconsin DOT
- Gregory Cohen, President, American Highway Users Alliance
- Jill Ingrassia, Managing Director, AAA

Freight Trends

- Gary Maring, Consultant, Cambridge Systematics/Future Interstate Consulting Team

Freight

- Michael Burton, President and CEO, C&K Trucking, LLC
- George Harry, Director, Global Transportation Organization (GTO), Johnson & Johnson
- Scott Perry, Chief Technology and Procurement Officer, Ryder Global Fleet Management Solutions
- Caitlin Rayman, Director, Freight Management and Operations, FHWA

- Russell Toney, Senior Vice President, Global Sourcing, Dover Corporation

Climate Change and its Potential Impacts on the Interstates

- Jennifer Jacobs, Co-Director, Center for Infrastructure Resilience to Climate, and Director, The Infrastructure & Climate Network (The ICNet), University of New Hampshire
- Don Wuebbles, Harry E. Preble Professor of Atmospheric Science, University of Illinois

U.S. Department of Defense Perspective

- Bruce Busler, Director, Joint Process Analysis Center, and Executive Director, U.S. Transportation Command (U.S. Department of Defense [DoD])
- Kristin French, Principal Deputy Assistant Secretary of Defense, and Acting Assistant Secretary, Logistics and Materiel Readiness, Office of the Secretary of Defense (OSD–DoD)

Chicago and Illinois Transportation Planning and Effects on the Interstate Highway System

- MarySue Barrett, President, Metropolitan Planning Council
- Randall Blankenhorn, Secretary, Illinois DOT

The Interstates and Economic Development

- Gail Grimmett, President, Travel Leaders Elite
- Ed Mortimer, Executive Director, Transportation Infrastructure, U.S. Chamber of Commerce

September 12, 2017
AT&T Executive Education and Conference Center
The University of Texas at Austin, Austin, TX

Texas and Dallas Transportation Planning and Effects on the Interstate

- James Bass, Executive Director, Texas DOT
- Michael Morris, Director of Transportation, North Central Texas Council of Governments (NCTCOG)

Highway Construction: Outlook and Innovation

- Daniel Filer, Vice President, Business Development, Ferrovial
- Narayanan Neithalath, Senior Sustainability Scientist, and Associate Professor, Arizona State University
- Peter Ruane, President and CEO, American Road & Transportation Builders Association (ARTBA)

Innovation and Institutional Partnerships

- Harriet Anderson Langford, President, The Ray C. Anderson Foundation
- Allie Kelly, Executive Director, The Ray

Social Equity

- Ron Hall, President, Bubar & Hall Consulting, LLC

Land Use

- Jody McCullough, Planner, Office of Planning, FHWA
- John Renne, Director, Center for Urban and Environmental Solutions, Florida Atlantic University

November 7, 2017
National Academy of Sciences, Keck Building
500 5th Street, NW, Washington, DC

Highway Safety

- Elizabeth Alicandri, Associate Administrator, Office of Safety, FHWA
- David Harkey, Director, Highway Safety Research Center, Highway Safety Research Center (UNC)
- Shaun Kildare, Director of Research, Advocates for Highway & Auto Safety
- Timothy Neuman, Senior Associate, Bednar Consulting, LLC

Governance

- Barry Seymour, Executive Director, Delaware Valley Regional Planning Commission (DVRPC)
- Walter "Butch" Waidelich, Executive Director, FHWA
- Frederick "Bud" Wright, Executive Director, AASHTO

Funding Allocation Process

- Kathy Ruffalo, Principal, Ruffalo and Associates, LLC

Appendix C

Vehicle-Miles Traveled: Trends and Implications for the U.S. Interstate Highway System

Steven E. Polzin

This appendix provides context for the historical trend of vehicle-miles traveled (VMT) and insight into how future conditions might influence travel demand on the U.S. Interstate Highway System. Transportation requires significant investments in infrastructure that often require significant lead times and produce a host of consequences, from changes in land uses and values to emissions and energy consumption to employment and economic opportunity, all of which are of interest to policy makers and the public. Thus, analysts have long sought to understand future travel demand sufficiently that investment and policy decisions can be implemented to respond to and influence that demand.

Although disclaimers are appropriate for any discussion of the future, it should be understood that the current pace of change and uncertainty regarding key factors that influence travel demand is unprecedented in the history of our Interstate System. Demographic and economic conditions continue to fluctuate, fuel price changes affecting travel demand continue to be dynamic, and uncertainties associated with these factors are exacerbated by the transformational changes in technology that are being developed and deployed. These changes and those anticipated will continue to have dramatic impacts on travel. For example, forecasts for self-driving vehicle deployment range from 5 to 50 years in the future and are hypothesized to reduce travel demand by 30 percent or increase it up to 50 percent. The range of consequences associated with evolving technologies is dizzying, with both positive and negative effects on travel demand. Telecommuting, e-commerce, online education, and electronic document transfer are examples of technologies reducing the need for travel. Simultaneously, technologies enable exposure to new travel destinations, provide opportunities for same-day deliveries, and create the prospect for lower-cost travel through vehicle sharing and reductions in the onerousness of travel by virtue of relieving the driver of the need to drive the vehicle—factors that can induce significant additional travel and affect safety. Visions of empty vehicles shuttling between assignments and low-cost travel in shared, electric, self-driving vehicles bolster scenarios of rapid increases in travel demand, with the fundamental economics of lower cost inducing additional consumption of travel.

This appendix first characterizes historic trends in VMT growth with specific attention to the Interstate System, and then addresses our understanding of what factors influence travel demand and discusses the demand growth and implications. Before venturing into discussions of the future demand for travel, it is helpful to reflect that despite massive intellectual and monetary investments, the record for forecasting election results, stock market prices, and consumer preferences for various products and media is less than stellar. Forecasting human behavior and all the underlying factors that influence it remains difficult. So, too, forecasting future travel demand is highly uncertain and challenging.

TRAVEL DEMAND TRENDS

Figure C-1 shows the long-term trend in VMT and national population since 1900. World War II and the two energy crises in the 1970s are the only noticeable fluctuations on the trend line until approximately 2005, and the subsequent dip and recent recovery have resulted in an unprecedented approximate 8-year pause in the upward trend in VMT. From 1945 through 2005, VMT increased nearly 12-fold, 4.23 percent per year on average, while population more than doubled, increasing 1.23 percent per year. During that same period, the annualized rate of gross domestic product (GDP) growth was 3.15 percent.

Seemingly reasonable extrapolations of these VMT growth trends resulted in numerous long-range plans produced in the 1990s and early 2000s that predicted gridlock levels of congestion and correspondingly large transportation infrastructure needs. The softening of VMT growth, empirically evident in aggregate VMT data in the early 2000s and hinted at by other data sources such as travel surveys even earlier, proved the undoing of the "sky is falling" forecasts and gave pause to the use of long-term VMT trends as the basis for future VMT forecasts.

Simultaneously, reflections on our theory of travel behavior have provided a logical basis for considering that fundamental trends in VMT were beginning and continue to change. The trend of women joining the formal workforce is substantially complete, an aging population influenced by the

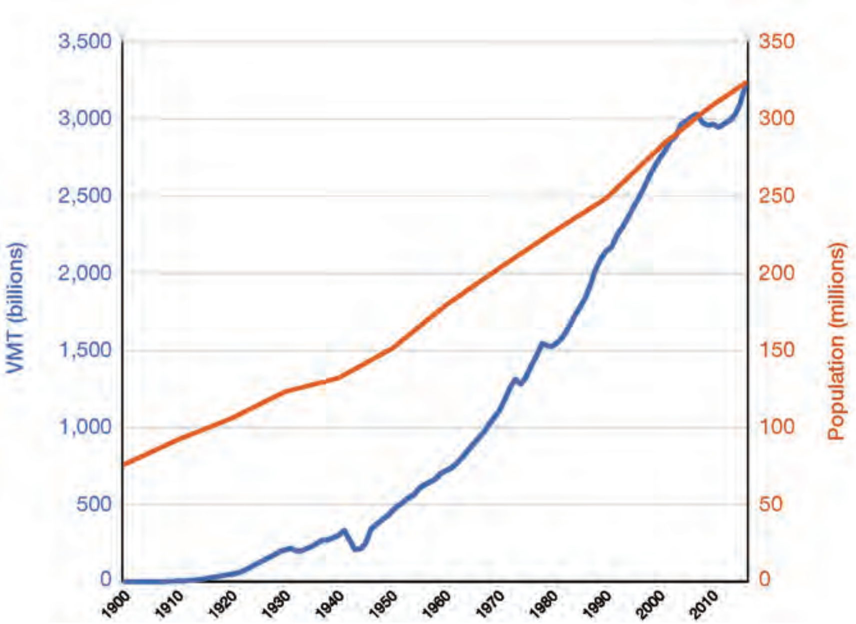

FIGURE C-1 National annual VMT trends and population trends, 1900–2016.
SOURCES: FHWA 2017; U.S. Census Bureau 2016.

large baby boomer cohort moving past their peak travel years has lessened their travel demand, auto availability levels have neared saturation, and the flight of urban residents to suburban areas may be playing itself out. Shifts from shared-ride travel, mass transit, and walk modes—some of the sources for increased VMT—have less room to drop (Polzin 2006). Substitution of communication for transportation (e.g., e-commerce, distance learning, social media for in-person communications, telecommuting, electronic dissemination of documents, and voice and video media) and globalization of manufacturing—in effect, exporting the VMT associated with transporting inputs to production—influence travel demand.

Between 1945 and 2005, VMT increased more than 45 billion miles per year, and in the next decade, VMT increased, on average, about 10 billion miles per year despite a meaningfully higher population. The bounce-back indicated by preliminary 2016 data shows an increase well over 100 billion miles and is the largest year-over-year increase ever posted. Although a recovering economy and lower fuel prices are often noted as the reasons for this, the changes in VMT since the late 1990s leave analysts with a great deal of uncertainty regarding future forecasts. As noted, this uncertainty is exacerbated by emerging trends related to the prospect of vehicle-sharing and self-driving vehicles.

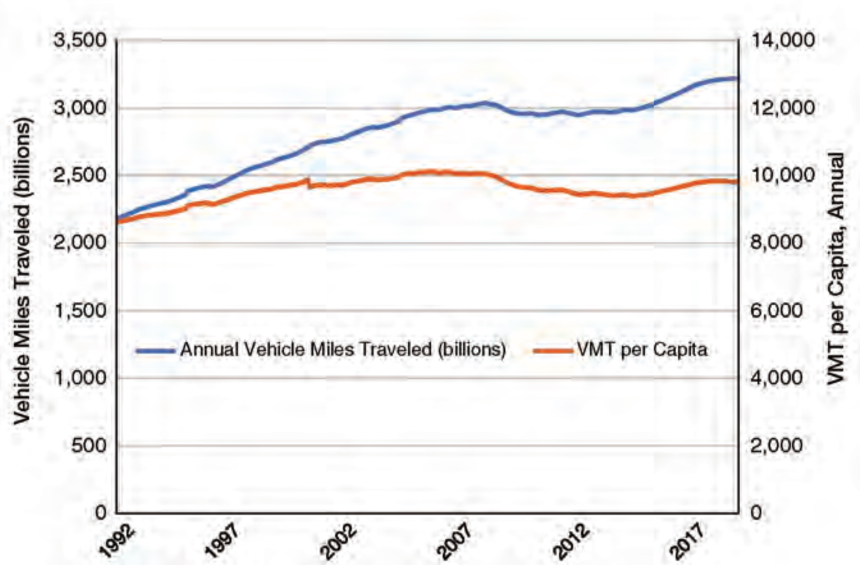

FIGURE C-2 National VMT and VMT per capita trend, moving 12-month total, 1990–2016.
SOURCES: FHWA 2017; U.S. Census Bureau 2016.

Figure C-2 shows the trend in VMT and VMT per capita since January 1992. As is apparent in the graph, VMT per capita remains slightly below its peak level in the 2003–2004 time frame, but total VMT has rebounded since the recession and is at all-time highs.

Figure C-3 reports monthly VMT and VMT per capita trends in terms of percentage change since January 1992.

Geographic Distribution of Travel Demand

The magnitude of the implications for the U.S. Interstate System of the new demand for transportation capacity is dependent on the geography distribution of increased travel demand. At the national level, it is common to talk about low single-digit percentage changes in demands or VMT. If we presume that they are uniform across the system, accommodating the increase in travel demand associated with the forecasted approximately 0.8 percent per year growth in population over the next several decades, it does not sound overwhelming.

However, growth in demand is not geographically uniform, and hence, the pressure for additional capacity will not be uniform. This results in

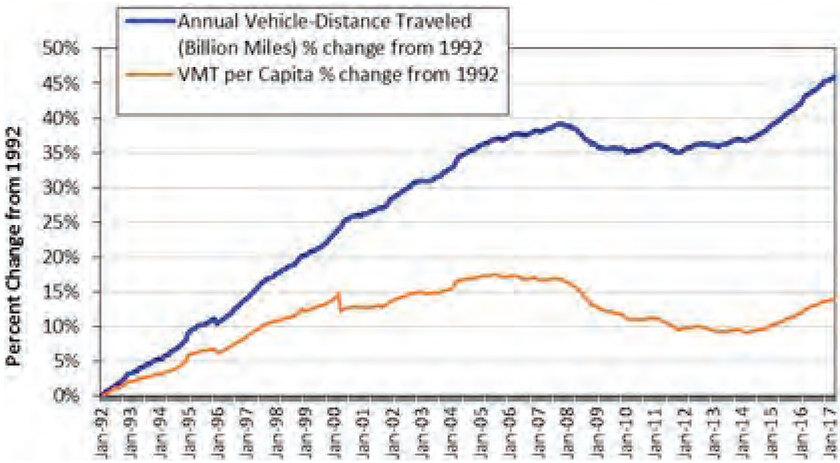

FIGURE C-3 National VMT and VMT per capita, percentage change from 1992.
SOURCES: FHWA 2017; U.S. Census Bureau 2016.

the consequences of demand growth being concentrated and more likely to require more significant capacity increases than can be tolerated or accommodated by incremental operations improvements of existing infrastructure. As an analogy, a 3-inch snow might be passable, but that same snow blown into 3-foot drifts requires plowing. The smaller the share of the system over which new capacity demands occur, the more likely it is to require substantive capacity increases to ensure adequate performance.

Other sections of this appendix speak to the various factors that affect demand on the Interstate System, but at the simplest level the geographic distribution of new population creates significant variation in new demands on the Interstate System. Additionally, the disparity of new demands is exacerbated in cases in which there is a geographic redistribution of existing population (some areas showing declining population), further influencing the magnitude of new geographic demand. This differential growth was outlined in Appendix E, and its implications in terms of infrastructure needs are enumerated below. Overall growth forecasts are noted in Box C-1. Whereas demands on the Interstate System are affected by many more considerations than just adjacent population, travel demand remains highly correlated with population. At the highest level of geography—Census regions—the population growth in 2000–2016 has been markedly different across geography. As shown in Table C-1, the historic trend of strong growth in the West and South has continued this century, with these regions growing approximately four times as fast as the Northeast and

BOX C-1
U.S. Population Projections

The Census Bureau develops long-range population projections, the most recent of which was in 2014 and goes through 2060. The rate of population growth declines over time in absolute annual increases from approximately 2.6 million per year currently to an estimated approximately 1.9 million per year in 2060. The increases range from approximately 0.8 percent per year currently to less than 0.5 percent per year in 2060. For context, there are currently approximately 688 lane-miles of Interstate for each million residents.

Approximately 41 percent of population growth in the United States since 2010 is attributed to net international in-migration. Going forward, future growth is projected to be even more dependent on net immigration; hence, it will be influenced by policy and economic conditions.

SOURCE: https://www.census.gov/data/datasets/2014/demo/popproj/2014-popproj.html.

TABLE C-1 U.S. Population Change by Census Region

Census Region	Net Change 2000–2016 (%)
Northeast	4.9
Midwest	5.5
South	22.0
West	21.3

SOURCE: U.S. Census Bureau 2016, Table B01003.

Midwest. When looking at the same issues at the state level, one state—Michigan—has shown a population decline since the beginning of the century. Six states— Arizona, California, Florida, Georgia, North Carolina, and Texas—collectively accumulated more than 50 percent of the national population growth.

Perhaps more relevant to the scale of transportation infrastructure needs is looking at growth trends at the county level, which provides additional insight regarding the distribution of population growth over geography. At that scale of geography, the disparity of growth rates and magnitudes is even more pronounced. In total, 12 percent of the 377 counties are responsible for more than 91 percent of the national growth in population since 2000. These counties each had growth in excess of 25,000 persons, suggesting pressure on the roadway and Interstate System in those counties and, most probably, the interconnection of those counties with adjacent geographic areas. Table C-2 enumerates the growth trends since 2000 for the counties and District of Columbia.

TABLE C-2 U.S. County Population Growth Trends, 2000–2016

Growth Category	Number of Counties	Sum of Change	Percentage of Counties	Percentage of Growth
Counties that grew more than 25,000	377	37,783,846	12.00	91.31
Counties that grew more than 5,000 to 24,999	439	5,160,638	13.97	12.47
Counties that grew more than 1,000 to 4,999	574	1,443,389	18.27	3.49
Counties that grew less than 1,000	457	189,584	14.54	0.46
Counties that shrank from 1 to 999	749	–325,475	23.84	–0.79
Counties that shrank from 1,000 to 4,999	472	–97,254	15.02	-2.41
Counties that shrank more than 5,000 to 24,999	59	–577,965	1.88	–1.40
Counties that shrank more than 25,000	15	–1,299,029	0.48	–3.14
Total	3,142	41,377,734		

SOURCE: U.S. Census Bureau 2016, Table B01003.

Notice that 1,295 counties—41 percent of the total—had declining population since the turn of the century, and 15 had declines of more than 25,000. These population declines would certainly suggest a lessening of pressure for transportation capacity expansion and, perhaps more significantly, undermine the economic base over which transportation infrastructure investments can be supported. Although the nonuniformity of growth exacerbates the criticality of a substantial capacity expansion, this need is further heightened in situations in which there is redistribution of the existing population (and corresponding travel demand). In the extreme, it creates the possibility of existing capacity in growth areas being overwhelmed while existing capacity in declining areas may be underutilized. Since 2000, national population has increased by 42 million—approximately 15 percent. In addition, net population relocation of approximately 8 percent of the population from declining counties to growing counties resulted in a total of a 23 percent increase in population occurring in 60 percent of U.S. counties, with the vast majority of that growth occurring in just 12 percent of the counties.

Figure C-4 is a visual representation of the geographic disparity of population growth across the United States.

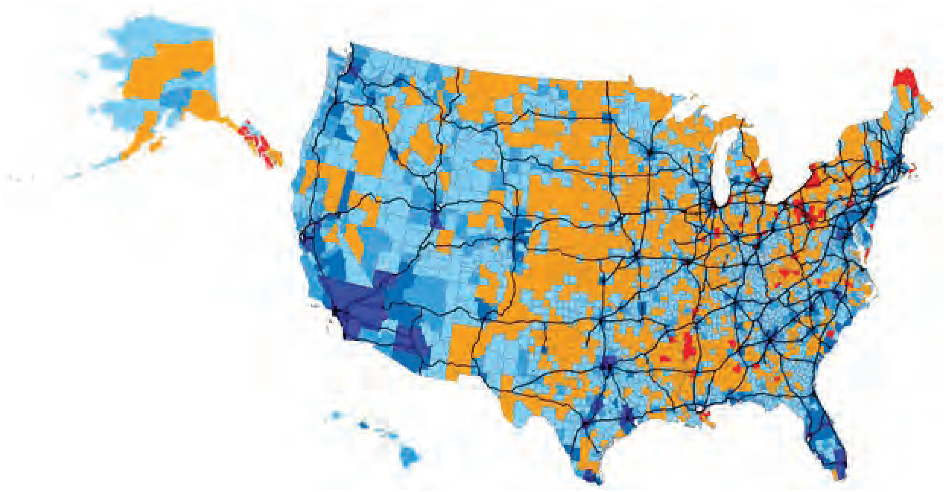

FIGURE C-4 Population growth variation across U.S. counties.
SOURCE: U.S. Census Bureau 2016, Table B01003.

Urban Versus Rural Interstate Demand

Insight into the nature of Interstate demand growth also can be gleaned from looking at the trends with respect to Interstate System availability and utilization in urban and rural areas. As can be seen from Table C-3, system extent and growth are greater in urban areas, and urban area Interstate System volume growth is substantially greater than for rural areas. Urban Interstates comprised 0.5 percent of centerline miles of roadways and 1.2 percent of lane-miles of the roadway system and carried 17.5 percent of the roadway system volume in 2015. Those shares all increased since prior periods.

Figure C-5 portrays the relative role of urban and rural Interstates in accommodating VMT. Part of the irregularity of the trends is due to the post–decennial Census recategorization of urbanized areas (more geography around growing metro areas is classified as urban). Nevertheless, the trends are relatively clear, with urban Interstates playing an increasingly important role in accommodating VMT while the role of rural Interstates is diminished in terms of share of volume.

Figure C-6 shows the trend in terms of VMT carried by the components of the roadway system. The role of the Interstate System has continued to increase over time. Interestingly, demand softened in approximately 2002–2007, whereas volume softened on the non-Interstate highways.

As Figure C-7 portrays, volume per lane-mile on the urban Interstate System indicates that it is approximately three times that on the rural

TABLE C-3 Changes in U.S. Interstate Extent and Use, 1980–2015

		Centerline Miles[a]	Lane-Miles[b]	VMT (millions)[c]
Urban Interstate	Change	9,848.1	56,279.5	379,944.3
	Percent	106.9	116.1	235.6
Rural Interstate[d]	Change	–2,914.9	–12,728.3	100,681.6
	Percent	–9.14	–9.7	74.53

[a]FHWA 2016b, Table HM-220. Includes 50 states and District of Columbia.

[b]FHWA 2016b, Table HM-260. Data are based on state highway agency estimates reported for various functional systems and include 50 states and District of Columbia. For 1980–1992, the Interstate system is based on 100 percent inventory; non-Interstate arterial and collector functional systems are estimated from sample data; urban and rural local functional systems are estimated assuming two through lanes. For 1993–1995, the Interstate system, other freeways and expressways, and other principal arterial functional systems are based on 100 percent inventory; minor arterial, urban collector, and rural major collector functional systems are estimated from sample data; rural and urban local and rural minor collector functional systems are estimated assuming two through lanes.

[c]FHWA 2016b, Table HM-202. Data based on state highway agency estimates reported for various functional systems; includes 50 states and District of Columbia.

[d]The decline in centerline miles and lane-miles for rural Interstate attributable to reclassification of roadway segments to urban. As urban areas expand, more geography is classified as urban.

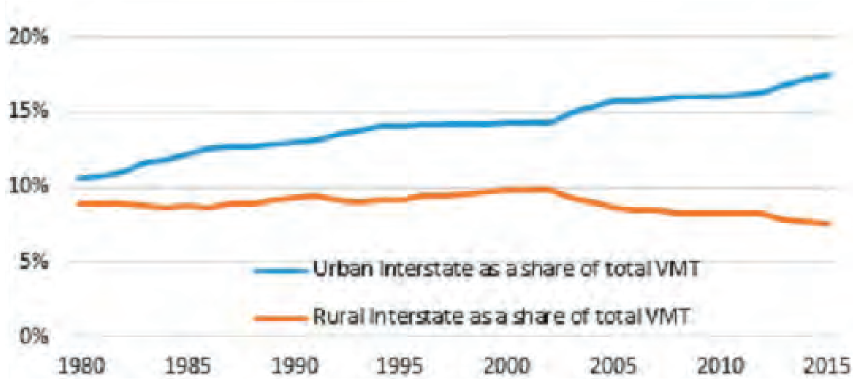

FIGURE C-5 Role of urban and rural Interstate highways in accommodating VMT.
NOTE: Data are based on state highway agency estimates reported for various functional systems and include 50 states and District of Columbia.
SOURCE: FHWA 2016b, Table VM-202.

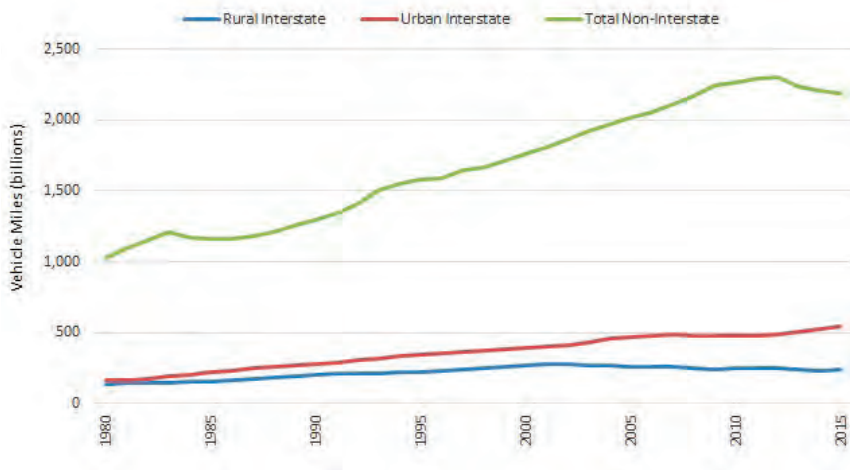

FIGURE C-6 Role of urban and rural Interstate in accommodating VMT.
NOTE: Data are based on state highway agency estimates reported for various functional systems and include 50 states and District of Columbia.
SOURCE: FHWA 2016b, Table VM-202.

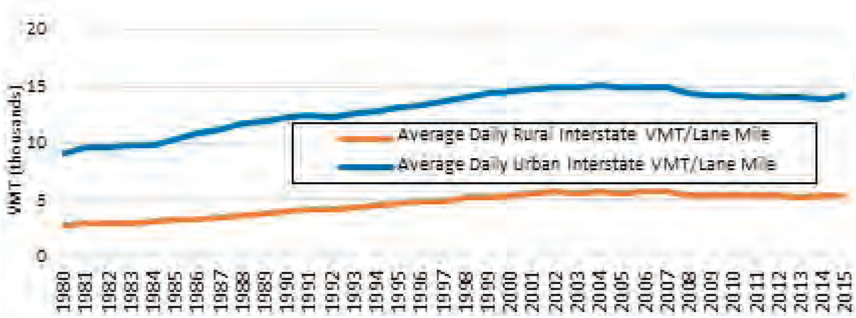

FIGURE C-7 Average daily VMT per lane-mile, urban and rural.
NOTES: Data based on state highway agency estimates reported for various functional systems; includes 50 states and District of Columbia. For 1980–1992, the Interstate system is based on 100 percent inventory; non-Interstate arterial and collector functional systems are estimated from sample data; urban and rural local functional systems are estimated assuming two through lanes. For 1993–1995, the Interstate system, other freeways and expressways, and other principal arterial functional systems are based on 100 percent inventory; minor arterial, urban collector, and rural major collector functional systems are estimated from sample data; rural and urban local and rural minor collector functional systems are estimated assuming two through lanes.
SOURCE: FHWA 2016b, Tables VM-202 and HM260.

system. In 1980–2015, the daily volume on each lane-mile of urban Interstate increased from 9,116 to 14,156, or 5,040 per lane-mile, a 55 percent increase. The rural Interstate volume increased from 2,826 to 5,462, about half as much—2,636 per lane-mile—but an increase of 93 percent. As of 2015, daily volumes remained approximately 5 percent below peak levels from the prior decade.

Implications of Nonuniform Distribution of New Demands for Capacity

Although this review provides insight into the potential geographic distribution of growth and transportation demand at the county level and between urban and rural areas, the fundamental issue of the geographic correspondence of transportation capacity relative to demand is relevant at a smaller geographic scale, as revealed by facility-specific demand forecasts.

Nonetheless, understanding the recent and forecast population distribution and subsequent transportation network impacts requires two key points. First, the distribution of demand across geography affects the nature and magnitude of capacity needs. Second, declines in demand in some geographic areas can exacerbate the challenges of accommodating growth, because some existing system links may have declining utilization whereas other areas might see dramatic increases in demand, accommodating both disproportionate shares of growth and redistribution of population.

The fact that demand growth has not been uniform across the Interstate System, nor is it likely to be in the future, has implications for future infrastructure needs. Need for new capacity is most likely to occur in urban high-growth areas—areas in which congestion, higher costs, and challenging right-of-way availability affect the ability to respond to growing demands.

Although this discussion is in the context of differential population growth, differential incidence of other conditions known to influence travel demand also may occur. For example, travel demand has long been correlated with economic health, and economic health may not be uniformly distributed by geography or population. Areas that are growing relatively wealthier might experience more rapid growth in travel demand. Differential trends in various sociodemographic characteristics related to travel demand, technology deployment, and other factors also might contribute to differential demand growth across the system.

Factors Influencing Travel Demand

In exploring future demand, it is important to touch on our understanding of factors that influence travel levels. The criticality of travel for social and economic interaction is well established in history and evidenced by the significant role that transportation plays in the economy and the fabric of society. It has been hypothesized that growth in travel demand associated with individuals is attributable to growth in income and growth in knowledge. As characterized in Figure C-8, growth in income and knowledge lead to specialization in consumption and activity or use of time, which leads to an increase in the demand for travel and communication. In contemporary terms, a homemaker receives training in a specialized skill area and joins the workforce. Her children are dropped off at daycare and laundry is dropped at the cleaners; prepared meals are purchased on the way home from work. Generic white bread at the local grocery is replaced with whole-grain bread from a more distant natural foods store. The circle of social relationships expands from adjacent neighbors to work colleagues and parents met through children's organized activities. The household has more highly specialized professional, consumer, and social activities, more income, and more travel.

This fundamental phenomenon has contributed to significant growth in per capita travel over the past decades and remains central to our understanding of growth in travel demand. However, beyond these fundamental drivers of demand, the supply and performance of travel options, and, more recently, the ability to substitute communication for travel factor into our considerations of future travel demand as, of course, does basic growth in population.

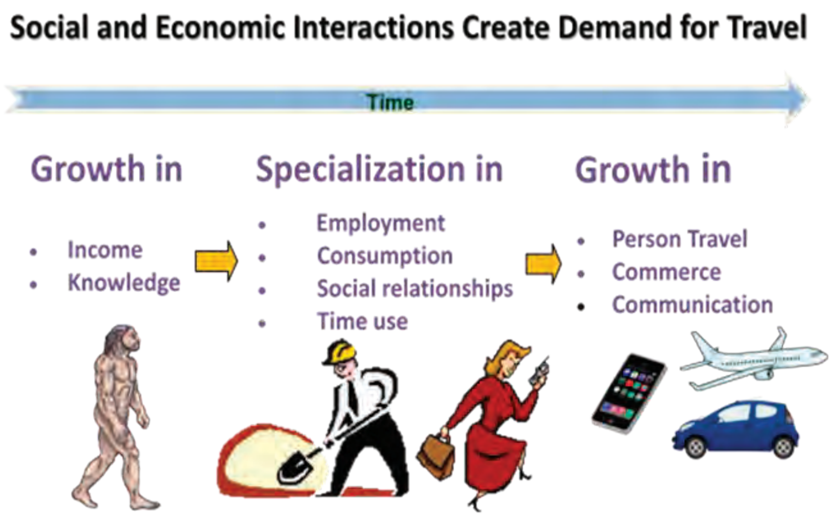

FIGURE C-8 Characterization of drivers of travel demand.

This section explores factors that researchers have identified as influencing the demand for travel. The objectives are to

1. Identify factors that are believed to underlie travel demand going forward,
2. Assess the degree of understanding of their influence on travel demand, and
3. Explore the state of knowledge regarding those conditions going forward such that we can speculate on the magnitude of their impact on travel.

As shown in Figures C-1 and C-2, U.S. historic trends in total roadway VMT and the trend in total VMT per capita have changed markedly since earlier in this century. A number of multidecade trends have played out or at least moderated significantly. This includes growth in real income, growth in auto ownership, suburbanization of population and employment, shifts from alternative modes to single-occupant auto, and growth in trip making accompanying income growth and labor force participation (Polzin 2006). Growth in travel demand decoupled from both population growth (see Figure C-1) and GDP growth (see Figure C-10) as changes in the economy, demographics, and technology altered long-term relationships. Trend extrapolation of linear relationships had served well for gauging future VMT but no longer appears appropriate. Perhaps more critical, there is a growing recognition that our understanding of travel demand was perhaps superficial and not up to dealing with emerging trends such as communication substitution for travel, new business models for delivering mobility, new demographic and economic conditions, rapid and significant fuel price changes, and policies and behaviors influenced by environmental and climate change considerations. This pace of change and uncertainty regarding the nature and magnitude of future travel demand heighten the desire to more fully understand future travel.

Figure C-9 represents one framework for discussing future travel and is intended to accommodate all types of travel that use roadways, including person and freight travel as well as commercial vehicles, tourists, etc. It is recognized that there are trade-offs between roadway modes and alternative travel modes (rail, air, water) for both passengers and freight movement.

In general, demand factors (blue boxes in Figure C-9) change relatively slowly because they include such factors as sociodemographic characteristics and land use distribution, all of which, at the national scale, do not change quickly, with perhaps the exception that culture and value factors could shift markedly in response to significant events. The demand factors shown in Figure C-9 are widely acknowledged in the transportation literature, with perhaps the exception of the box embracing business,

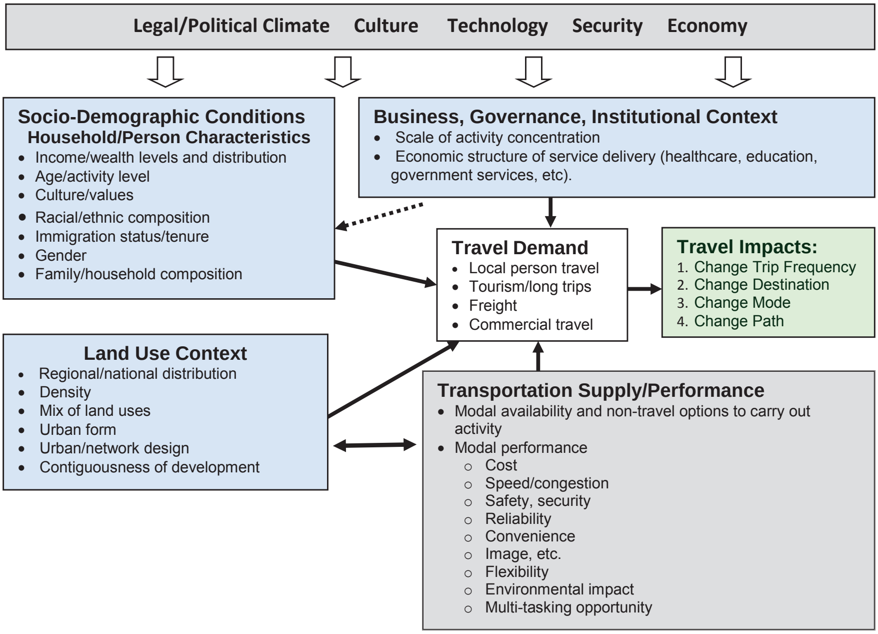

FIGURE C-9 Framework for exploring factors influencing travel demand.

governance, and institutional context. These factors are known to influence travel demand and mode choice, hence providing a basis for forecasting future demand. Supply factors (shown in the gray box) include characteristics of the transportation system and reflect important factors such as fuel cost, which influences demand.

Table C-4 itemizes the estimated breakdown across vehicle types and urban/rural contexts. The best available evidence of the composition of roadway travel demand indicates that approximately 76 percent of national VMT is attributable to household-based person travel, 10 percent to heavy freight travel, 2 percent to public vehicles (e.g., school buses, police cars, emergency response vehicles), and 12 percent to commercial vehicles, which include local freight distribution vehicles, utility vehicles, and vehicles providing services from package delivery to lawn services.

Relationship of Supply and Demand

It is not uncommon for policy makers to seek insight regarding future travel demand or VMT while implicitly or explicitly presuming that demand can be determined independent of transportation supply. In reality, a host of characteristics, such as time and money cost of travel and available mode

TABLE C-4 Shares of Vehicle-Miles Traveled by Market Segment

	Light Vehicles (%)				
	Household Based	Public Vehicle, Utility, Service Based	All Light Vehicles	Heavy Vehicles (%)	Total (%)
Urban	55.52	9.04	64.56	5.45	70.0
Rural	21.90	3.56	25.46	4.54	30.0
Total	77.42	12.60	90.02	9.98	100.0

SOURCES: AASHTO 2013, Table 2-1; FHWA 2015, Tables VM2 and VM4.

choices, are elements of supply that will influence travelers' actual extent and means of travel. As with consumption of any product or service, there is interplay between supply and demand. Most obviously, cost to travel in both time and money influences the demand for travel. This fundamental metric remains extremely relevant in an era in which energy prices are fluctuating dramatically, technology may increase auto costs significantly, or alternatively, shared use may reduce auto costs, as might reductions in insurance, medical, or property damage costs attributable to technology improvements enhancing safety. Additionally, the prospect that automation will enable travelers to use in-vehicle travel time for purposes other than driving could influence perceived travel costs significantly. Meanwhile underinvestment in infrastructure and transportation services could result in roadway conditions and congestion that could increase travel time and vehicle operating costs.

Other aspects of supply also influence demand. For example, the introduction of or improvements in transit can increase travel by individuals who do not have private-vehicle mobility options. The prospect of self-driving vehicles is hypothesized to increase travel for those who might be precluded from driving due to mental, physical, or legal/age constraints on driving.

Critical aspects of the boxes in Figure C-9 will be discussed in sections below focusing on those factors believed to be most significant influences on future VMT.

Sociodemographic and Economic Conditions

The traditional focus of VMT forecasting has centered on sociodemographic and economic conditions and travel behavior. This area remains relevant to issues such as an aging population, urbanization, differential millennial behaviors, income distribution, increased diversity, and other factors influencing travel behaviors and travel demand levels. The significance of the geographic distribution of growth was discussed previously.

VMT and Economic Activity

Not surprisingly, VMT is highly correlated with economic activity. As shown in Figure C-10, the long-term trend in GDP and VMT are highly correlated. Understanding the importance of this relationship is helpful in forecasting VMT; however, the difficulty in forecasting GDP is widely recognized, and hence, understanding the strong relationship is not necessarily helpful, absent a way to forecast GDP with confidence. The challenge is compounded by evidence that the GDP–VMT relationship has started to change over the years, with VMT growth not as strongly correlated with GDP. The growth in information and service industries, which are less transportation-intensive than are other industries, is likely contributory to this weakening relationship. Table C-5 itemizes the importance of transportation to various industry categories. The economic sectors that have been and are predicted to continue growing strongly tend to be less transportation-intensive—factors that contribute to the lessening significance of GDP to VMT levels.

As noted in Table C-4, the vast majority of VMT comprises household-based travel as individuals carrying out social and economic activities.

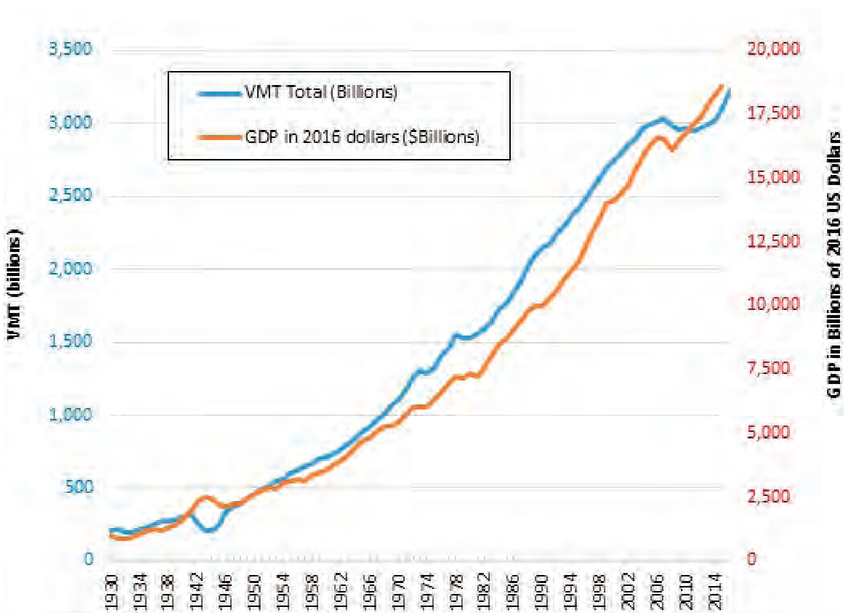

FIGURE C-10 National VMT and GDP trends.
SOURCES: BEA 2017 (current-dollar and "real" GDP table); FHWA 2016b, Table VM-202.

TABLE C-5 Transportation Intensiveness of Economic Sectors

Sector	Amount of Transportation Required to Produce $1 of Output (2014)	Contribution to GDP (2015, billions)
Natural resources and mining	4.2¢	$500.9
Utilities sector	4.6¢	$288.3
Construction	3.8¢	$716.9
Manufacturing	3.7¢	$2,167.8
Wholesale and retail trade	9.9¢	$2,130.1
Service		$9,291.7
Information	1.5¢	
Financial	0.8¢	
Professional/business	2.8¢	
Education and health	1.6¢	
Leisure and hospitality	3.2¢	
Other	2.9¢	
Government	4.7¢	$2,323.6

SOURCE: BTS 2015.

Household income is highly correlated with travel levels, as income relates to workforce participation (commuting trips) and work-derived income enables the social and retail activities that drive household travel demand. Household survey data indicate that the moderation in household travel demand was associated with those households in which resource constraints appear to be more critical to constraining travel demand. Low- and moderate-income households—households that have not seen real income growth—have had their travel demand influenced by economic conditions. Figure C-11 shows the relationship between household income for the bottom 80 percent of households and national total VMT. As is apparent, there is a strong correlation between household income in this 80 percent of households and total national VMT. These households may have latent demand for additional travel should more household income become available. Travel-generating activities such as vacations, shopping, recreation, and eating out are highly related to discretionary income and, should income growth ramp up for this large share of the population, VMT would expand more rapidly.

Collectively, the implications of Figures C-10 and C-11 is that future VMT will be influenced by the nature of business growth and by the distribution of income across the population. Should various activities such as increased manufacturing activities, growth in infrastructure investment, higher minimum wages, or economic growth that results in inflation-beating income growth for low- and moderate-income households occur, the VMT impact may be more pronounced than if current trends continue.

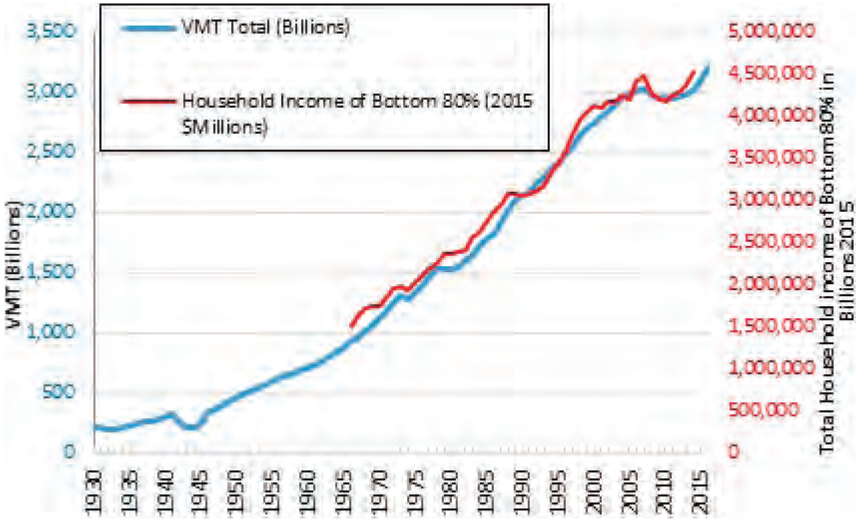

FIGURE C-11 National VMT and household income of bottom 80 percent of U.S. households.
SOURCE: FHWA 2016b, Table VM-202.

Population Characteristics and Travel Behavior

Changing population characteristics, specifically the movement of the large baby boom cohort toward retirement and the entrance of the even larger millennial generation into young adulthood, have been the basis for significant speculation regarding travel demand implications. Aging baby boomers are passing their peak travel years (ages 35–55) and entering the point in their life cycle when travel declines. Declining baby boomer travel demands may be associated with less travel in support of dependent household members (more likely to be empty-nesters), the prospect of no longer commuting in retirement, and the prospect of declines in physical stamina, discretionary income in retirement, and diminished motivation to accumulate material items. This generation of older adults has higher licensure levels and greater travel levels than prior older adult generations, but diminished travel from earlier in their life.

Toward the other end of the age spectrum, millennials have evidenced notably different travel levels than prior generations of young adults, affected by significantly higher levels of pursuit of advanced education and delays in marriage, household formation, starting families, and beginning careers. This age cohort is substantially more urban than prior generations and has markedly higher levels of continuing to live in a parent's household. They use social media to satisfy some of their social interaction needs and substitute communications for travel via online shopping, downloading music and videos, and interactive video gaming via the Web. This generation reached adulthood during a recession and, in many cases, accumulated substantial education debt, which slowed their pace of attaining vehicles and independent living. More recent data as the millennials age and the economy improves suggest that this generation is evolving toward more typical travel characteristics as they age and as economic constraints to travel and more travel-intensive lifestyles are diminished. The extent to which their behaviors will continue to vary from historic norms remains to be seen, as does the extent to which subsequent generations will have different travel behaviors. As always, caution should be taken in generalizing behavioral differences across contexts because there is a great deal of diversity within the millennial generation in education levels, residential locations, and travel behaviors.

Historically observed race and ethnicity differences in travel might lead to the expectation of moderation in travel demand as the population becomes more diverse. However, many of the travel behavior differences across populations are better explained by location decisions and economic status, because residual differences attributed to race and ethnicity have become more modest over time. Travel behavior predominantly reflects economic conditions and the land use and transportation context. As additional data are assembled and the full impact of the recent economic conditions are more comprehensively understood, forecasters will have a stronger basis on which to gauge the impacts of changes in the sociodemographic composition of the population.

Land Use Context

One of the more powerful influences on travel behavior is the intensiveness of activities or the density and mix of land use. As noted in Figure C-9, a variety of traits associated with land use influence travel. Most obviously, the distance of travel required to access various activities is lessened in environments with more intensive development. Although some of the advantage of proximity is offset by the prospect of additional destination choices spurring more travel, it has long been recognized that routine household-serving activities and their associated travel are minimized in more densely developed urban environments. In addition, these environments make alternative travel means such as biking, walking, and public transit more viable thus further mitigating VMT.

Table C-6 summarizes differential per capita VMT for the age 20–39 cohort based on residential location type. These data do not adjust for income or other considerations including self-selection but clearly communicate the differential VMT per capita as a function of land use intensiveness.

TABLE C-6 Per Capita VMT by Location Type

Urban Continuum	Daily VMT per Capita (Ages 20–39)
Urban	18.0
Second city	23.1
Suburban	27.1
Town and country	32.7
Location in Urbanized Area	
In an urban area	24.1
In an urban cluster	25.7
In an area surrounded by urban areas	32.9
Not in urban area	35.2
Size of Urbanized Area	
1 million + with subway or rail	20.2
1 million + w/o subway or rail	25.8
500,000–999,999	27.9
200,000–499,999	24.7
50,000–199,999	25.9
Not in urbanized area	32.4
Urban/Rural	
Urban	24.3
Rural	35.2

SOURCE: Polzin et al. 2014.

As alluded to in Figure C-9, a host of characteristics of land use, including mix of activities, nature of the transportation network, physical design of transportation elements, presence of alternative mode options, and other factors contribute to the portfolio of land use–related characteristics that collectively influence travel.

The economic characteristics of business and government also influence travel. The trend toward more-specialized activity types and larger-scale facilities (schools, hospitals, retail centers, etc.) offset some of the proximity advantages of more intense development. Similarly, urban land rent distributions can offset the benefit of intensive development by forcing separation of activities by income levels (low-wage service workers travel long distances for employment because of lack of affordability of nearby residential locations).

In the context of long-range VMT forecasts and Interstate highway travel demand, continued urbanization suggests downward pressure on VMT growth. However, the large declines in rural population may have played themselves out, and the full VMT impact of travel patterns within emerging megaregions with continued activity specialization and housing affordability considerations may dampen some of the VMT savings historically associated with urban development patterns. As public housing is dispersed and new high-density central city development often is targeted to high-income residents, historic empirical relationships between density and travel may be changing.

Influence of Transportation Supply and Performance

The gray box in Figure C-9 itemizes aspects of transportation choices and characteristics that influence the demand for travel. Figure C-12 characterizes, in greater detail, factors that are frequently recognized as things that influence travel behavior.

In reality, the amount of travel both in total and on the Interstate Highway System will be influenced by the characteristics and performance of the system and of the alternative choices available to travelers as noted in Box C-2. Of course, one choice is to travel less. If the cost of transportation is particularly high in either time or money, travelers may choose to forgo trips, make shorter trips to closer destinations, group trips into chains, or travel on different modes or paths. Thus, the demand on the Interstate System will depend on everything from the price of fuel to the relative congestion on the Interstate versus parallel arterials to the presence of a transit alternative or the opportunity to substitute communication for travel.

Although a multitude of factors make predicting travel demand complicated and context specific, there is a generalized understanding of how demand responds to the critical factors of changes in travel in terms of cost of both money and time. These relationships, referred to as the elasticity

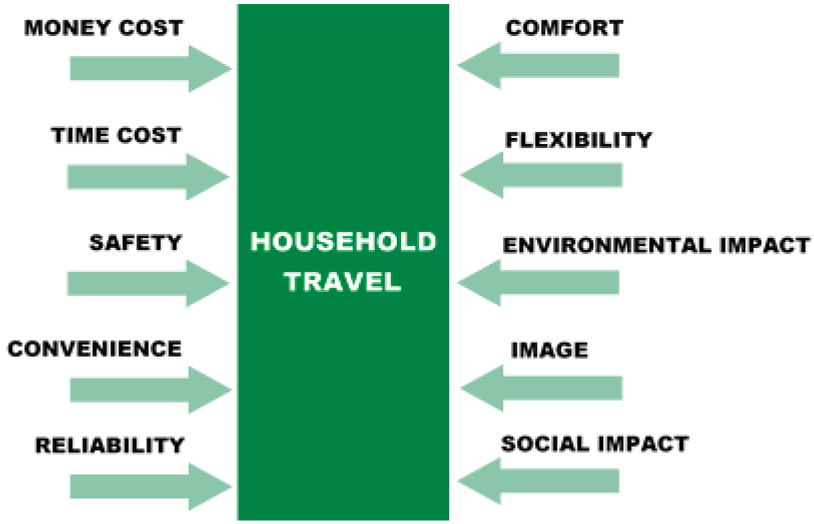

FIGURE C-12 Characteristics that influence travel decisions.

BOX C-2
Generic Travel Choices When Faced with Higher Travel Costs

- Forgo travel or substitute communication for travel.
- Reduce travel extent by choosing closer destinations or chaining trips together.
- Shift travel time (e.g., peak hour to off-peak).
- Choose different travel path (e.g., highway or arterial versus Interstate System).
- Choose different means of travel (e.g., shift from driving to riding as passenger with others, flying, transit/rail, or bike).

of demand as a function of cost and time, compare the percentage change in travel demand in relationship to the percentage change in travel cost or travel time. These relationships give insight into how changes in travel time associated with congestion or circuity (less direct travel path) or changes in travel cost associated with such things as tolls or higher fuel costs might affect demand. They also give insight into the travel consequences of deteriorating performance of the Interstate System should that translate into more congestion (slower travel time equals higher travel cost). In a broader context, cost-competitiveness of Interstate travel will be influenced by other considerations such as the competitiveness of airline, intercity rail, and intercity bus travel options and the comparative performance of rail freight versus truck travel choices. Additionally, the extent to which automated vehicles change the travel costs and perceived onerous of time spent traveling for future urban and intercity travelers will also influence the cost-competitiveness of Interstate travel.

Box C-3 highlights the concept of induced travel, explaining the concepts and the magnitude of the consequences. Given congestion levels on much of the urban Interstate System, these data suggest that significant additional Interstate VMT would accompany strategic capacity expansions.

Time and money cost of travel are recognized as very significant in explaining the mode and amount of travel. Fuel costs are recognized as one of the important cost considerations. Box C-3 reflects research findings on how fuel prices affect VMT. Other vehicle ownership and use costs such as the capital cost of vehicles, financing costs, maintenance costs, and parking and other associated costs also can contribute to decisions on owning and using vehicles. Affordability of insurance in urban environments may be among the factors that affect licensure and driving rates for young people. Similarly, urban environments in which there are parking costs at many destinations, and particularly if there are marginal costs associated with parking a vehicle at one's place of residence, can deter vehicle ownership and use.

BOX C-3
Induced Travel

Induced travel is the increase in usage of a transportation facility due to a reduction in the cost of travel that results from external changes (e.g., capacity expansion to an existing highway). The basic economic theory of supply and demand explains the existence of induced travel: adding capacity decreases travel time and lowers the cost of driving; when the cost of driving goes down, the quantity of driving goes up.

Induced travel includes both newly generated travel and travel diverted from other travel paths or destinations. The nature and degree of induced travel may differ in the short run versus the long run. In the short run, generated travel includes longer trips and new trips, and diverted travel includes shifted trips from other routes, times, and modes. In the long run, activity location changes may occur as a result of capacity expansion, and these locational changes can lead to additional travel.

The degree of induced travel differs not only between the short versus long runs but also across different scales. If the subject is a single facility, induced travel will appear large in relation to previously existing traffic because induced travel includes both generated travel and travel diverted to the now superior facility. At the regional level, however, induced travel would be smaller as the impact of diverted travel is netted out. At the same time, however, the amount of generated travel due to expanding a single facility is bigger at the regional level because the larger geographic area captures additional generated travel on feeder routes that tie to the expanded facility.

The degree of induced travel depends on the level of congestion on the subject facility before expansion. If there is not latent demand, as evidenced by congestion, there will be no induced demand. Induced travel in general is greater from expanding a facility that is more congested.

A large of body of empirical evidence confirms the existence and magnitude of induced travel in the case of highway travel at the regional or state levels. A recent review of the evidence suggests a range of 0.3–0.6 for the short-run elasticity of VMT with respect to highway lane-miles. This indicates that a 100 percent increase in roadway lane-miles could result in a near-term 30–60 percent increase in VMT. The long-run elasticity is estimated to range from 0.6 to 1.0, indicating that roadway expansion in congested environments might ultimately produce 60–100 percent more VMT as travelers take advantage of the new capacity in the short term and perhaps made residential and travel destination decisions in the long term that further increased their travel.

Because of the existence of induced travel, congestion reduction from a given capacity expansion would be lower than otherwise. That is, travelers may still enjoy faster travel but not as fast as they may have expected. At the same time, however, travelers can benefit from traveling at more preferred times and modes, taking more preferred routes, going to more preferred destinations, doing more preferred activities, living and working at more preferred locations, etc. Similarly, freight and commercial traffic would benefit from the enhanced mobility as well.

SOURCES: Handy and Boarnet 2014; Lee 2002; Noland and Hanson 2013; Pickrell 2001.

Time cost of travel is relevant to future travel demand in two importance ways. First, roadway congestion associated with demand outgrowing capacity can result in additional travel time expenditures by travelers. This additional cost can deter the extent of travel and result in various decisions that would dampen VMT. Researchers have estimated the elasticity of travel with respect to changing travel time as being approximately –0.5 (see Box C-4). For example, a 10 percent increase in travel time to work because of growing congestion on the roadway would be expected to reduce VMT by 5 percent.

The second major aspect of travel time relevant to future forecasts of demand relates to the prospect that in an era of self-driving vehicles, travelers would consider time spent traveling less onerous if they were able to carry out other activities such as sleeping, reading, or pursuing work or entertainment via a digital device. This has been hypothesized to create significant additional travel, because travelers are more willing to make travel and location decisions that increase travel if they can spend their travel time in more productive pursuits than driving. This issue is discussed in the section below on the impact of self-driving vehicles on VMT.

As noted in Figure C-10, other transportation system or mode considerations also influence the amount and mode of travel. Relative energy efficiency, relative safety, reliability, flexibility, social impacts, and other factors influence travel behavior. Modal safety has generally been improving as has energy efficiency. To the extent that new technologies can continue to improve performance and mitigate the negative consequences of travel (safety, energy use, emissions, noise, etc.), one might expect a positive bias

BOX C-4
Travel Time Elasticity of VMT

Short-run:	−0.38	Long-run:	−0.68

SOURCE: Lee and Burris 2005, C-14

Short-run:	−0.5	Long-run:	−1.0

	Urban	Rural
Short-run	−0.27	−0.67
Long-run	−0.57	−1.33

SOURCE: Litman 2017, 48.

toward greater travel. Some of these aspects are further elaborated on in the discussion of self-driving vehicles.

Impact of New Technologies and Self-Driving Vehicles on Future Travel Demand

This topic area is critical to understanding future VMT. Most unique about self-driving is the fact that it is hypothesized to influence travel demand by virtue of changing both the time and the monetary cost of travel as well as by changing the capacity of the transportation infrastructure system. Thus, the consequences of automation and self-driving are complex and uncertain. In addition, well-credentialed experts have dramatically varying perspectives on the time frame, pace, and consequences of deployment. A host of issues ranging from the pace of technology development and refinement to the legal and political context for deployment to market acceptance and economic considerations are likely to influence the magnitude of the impact of technology on transportation. Figure C-13 and Box C-5 highlight some of the anticipated consequences of additional technology deployment in transportation. The complementary and competitive nature of the various impacts contribute to the complexity and uncertainty of understanding the ultimate impacts. The cost change factors can influence both the total quantity of travel as well as the modal distribution. Mobility services (transportation network companies or driverless vehicle services) will be competing with public transit, traditional traveler-owned and -driven vehicles and perhaps shared-ownership vehicles for urban trips. There is also likely to be competition for short- to moderate-distance intercity bus, rail, and short-haul air services.

Various research initiatives have begun to explore the possible consequences of automation on travel demand; Table C-7 enumerates several of these studies. Most often, the studies test scenarios of various conditions and deployment extent to gauge the transportation consequence. As the VMT impact column indicates, results vary widely. In addition, the vast majority of discussions of self-driving vehicles are restricted exclusively to local household-serving person travel. Public and commercial vehicle travel, freight travel, and long-distance travel seldom are incorporated into the respective analyses. The reported results would be relevant only in the context of urban environments and household-based travel.

Freight and Commercial Traffic Travel Demand

Somewhat distinctive from person travel, freight and commercial travel demand can be affected by different factors. Heavy freight constitutes approximately 10 percent of total VMT, and the remaining commercial and

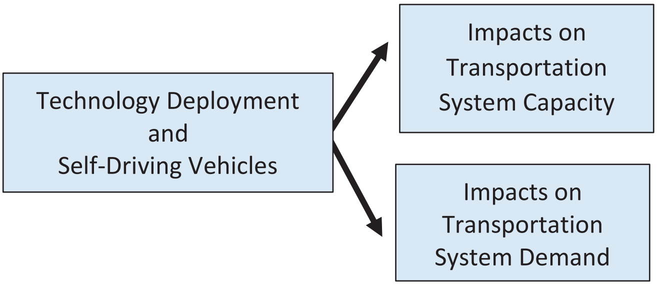

FIGURE C-13 Anticipated consequences of additional technology deployment in transportation.

public vehicle travel contribute an additional 14 percent. The impact of this VMT is disproportionate to its share of travel by virtue of the fact that these typically larger vehicles, with slower acceleration and deceleration characteristics, have higher levels of energy use and emissions and influence roadway capacity and condition considerably more than do individual personal vehicles.

Many of the same considerations that influence person travel will similarly influence freight and commercial travel activity. Demographic distribution, economic conditions, congestion levels, fuel price, intermodal competition, and the prospect of automation are factors that will influence future freight travel demand. Given an advanced economy in which economic growth is strongest in service and information areas, it is unlikely that growth in freight and commercial travel demand will vary dramatically from growth in person travel. In the opinion of this author, the greatest risks for differential growth in roadway freight demand will occur if economic conditions enable broad adoption of very quick deliveries; if the fundamental role of the United States in the global economy with respect to mining, manufacturing, and agricultural production changes significantly; or if technologies incentivise significant mode shifts—for example, from rail shipments to truck trains. Regional and facility-specific high-volume longer-distance roadway freight volumes will be influenced substantially by broader logistics and business strategies relating to intermodal and warehousing facility locations. Thus, geography-specific assessment of freight roadway volumes will be critical in appropriately accounting for freight impacts on Interstate VMT, and, even then, private-sector market decisions may affect line-haul volumes; for example, a business decision of a large international logistics firm in the business of consolidating global freight might significantly alter the volumes emanating from a given port, terminal, or warehousing location.

BOX C-5
Technology Impacts on Transportation System Capacity

- Greater vehicle occupancy—hence, fewer vehicles required—by virtue of technology-enabled ridesharing;
- Increased volume by virtue of minimizing incidents and incident delays/congestion;
- Increased volume by virtue of smoothing vehicle flow, which increases throughput;
- Increased volume by virtue of closer following distances;
- Increased volume through optimized intersection signal systems and lane management;
- Increased throughput by virtue of narrower lanes, enabling additional vehicle capacity/lanes on some facilities;
- Optimized vehicle logistics/trip circuity via navigation capabilities;
- Reduced travel via substitution of communication for travel;
- Increased travel via empty shared self-driving vehicles shuttling between vehicle assignments, parking, and service terminal locations;
- Increased travel via reduced travel money cost:
  - reduced insurance costs for safer vehicles,
  - reduced vehicle capital cost by virtue of sharing capital asset among multiple travelers,
  - reduced vehicle operating cost by virtue of sharing trips with multiple occupants,
  - reduced vehicle operating cost by virtue of electrification and logistics optimization anticipated for mobility service providers,
  - reduced parking/storage costs by virtue of vehicle sharing,
  - reduced per mile travel roadway infrastructure cost by virtue of greater utilization of facility via self-driving vehicles;
- Decreased travel via increased travel money cost:
  - increased vehicle capital cost due to inclusion of additional technologies and quicker obsolescence,
  - increased transportation infrastructure cost as infrastructure is modified to accommodate connected and automated vehicles,
  - increased travel cost if monopoly mobility service providers extract high profits from mobility services,
  - increased travel costs should reliance on mobility services require contingency investments to accommodate special situations such as emergency evacuations or operations in inclement weather;
- Increased travel via reduced travel time "cost":
  - reduced time cost by virtue of being able to do something of higher value during travel,
  - reduced time cost by virtue of faster travel speeds on managed or higher-capacity facilities;
- Decreased travel via increased travel time "cost":
  - increased travel time cost by virtue of vehicle arrival wait time and trip circuity for shared travel,
  - increased travel time cost by virtue of slower travel speeds due to induced travel from lower travel monetary costs,
  - increased travel time cost by virtue of slower travel associated with strict speed limit requirements and conservative vehicle interface behaviors.

TABLE C-7 Research on VMT Impacts of Automation

Reference	Primary Variables	VMT Impact (%)
Auld et al. 2017	100% automated vehicle (AV) penetration, 75% value of time reduction, +77% roadway capacity	+28
Childress et al. 2015	65% value of time reduction, –50% parking cost, per mile auto cost of $1.65	–34.5 to +19.6
Correia and van Arem 2016	Free parking, 50% value of time reduction	+17 to +49
Corwin et al. 2016	AV adaption and sharing	+25
Gucwa 2014	50% value of time reduction	+14
Fagnant and Kockelman 2014	Impacts of circuity and deadhead miles only	+11
Harper et al. 2016	Induced demand from persons with mobility constraints	+14
International Transport Forum 2015	Simulation, mode shifts	+6.4 to +90.9
KPMG 2015	Vehicle occupancy scenarios and demographic changes	Up to +130
Trommer et al. 2016	Reduced value of travel time, reduced travel time, lower cost of driving to 32% AV penetration	+3–9
Wadud et al. 2016	Cost of travel	+60

Forecasts of Future VMT

Numerous research efforts have explored modeling VMT trends in an effort to understand future infrastructure needs, energy use, vehicle emissions, traffic accidents, and other considerations impacted by travel demand. Because demand is influenced by a multitude of factors, various strategies and components of demand can be modeled through a number of different means. Despite these numerous strategies, forecasters remain stymied by an inability to predict the fundamental input assumptions for many known explanatory variables such as GDP growth and energy pricing, to say nothing of trends in technology evolution and deployment and human travel behavioral changes. Few forecasters predicted the moderation in demand growth that started in the early 2000s, and even fewer predicted the magnitude of the bounce-back of the past few years.

One of the widely cited uses of VMT forecasts is in identifying potential needs for infrastructure expansion. The *Bottom Line Report* series from

American Association of State Highway and Transportation Officials (AASHTO) exemplifies that use. Based on empirical trend analysis and judgment, this method accommodates uncertainty by using scenarios to frame future infrastructure needs. That report specifically referenced scenarios with 1 percent per year and 1.4 percent per year rates of national growth in VMT (see Box C-6). Another significant report for Congress, the *2015 Status of the Nation's Highway Bridges and Transit: Conditions and Performance* (C&P Report), also addresses the issue of future VMT as a basis for understanding future system performance. That report referenced a national level forecast of 1.04 percent per year (FHWA and FTA 2016; see Box C-7).

The Federal Highway Administration and Department of Energy develop various VMT forecasts for components of the total vehicle demand. Those forecasts disaggregate demand by vehicle class, are sensitive to various different input variables, and have various update frequencies and forecast time frames. A summary of some of these forecasts and their features are contained in Box C-8.

BOX C-6
National Growth in VMT

An annual investment of $120 billion for highways and bridges between 2015 and 2020 is necessary to improve the condition and performance of the system, given a rate of travel growth of 1.0 percent per year in vehicle miles of travel, which has been AASHTO's sustainability goal and which represents the likely impacts of both population growth and economic recovery.

If travel growth is at 1.4 percent per year, which carries forward the rate employed in the 2009 Bottom Line and is consistent with the long-term trend from 1995 to 2010 and has been indicated in recent months, then needed investment to improve the highway and bridge systems will be $144 billion per year.

SOURCE: Pisarski and Reno 2015, 2.

BOX C-7
Future VMT as a Basis for Understanding Future System Performance

Treatment of Traffic Growth[a]

For the Highway Economic Requirements System (HERS) analysis in this report, growth in VMT is based on two primary inputs: HPMS section-level forecasts of future annual average daily traffic that states provide and a national-level forecast developed from a new FHWA model. The national-level forecast serves as a control, which the sum of the forecast section-level changes in VMT must match. To match the national-level control, the section-level forecasts are scaled proportionally. For this report, the sum of the section-level forecasts yielded an aggregate average annual VMT growth rate of 1.42 percent that exceeded the national-level forecast of 1.04 percent per year and thus were scaled proportionally downward to match the national-level forecast.

The national-level forecast includes separate VMT growth rates for light-duty vehicles, single-unit trucks, and combination trucks; these separate growth rates were applied in the HERS analysis. VMT in light-duty vehicles is forecasted to grow at 0.92 percent per year. VMT for heavy-duty vehicles is forecasted to grow at a rate more than twice that for light-duty vehicles (2.15 percent per year for single-unit trucks and 2.12 percent per year for combination trucks). The higher rate of forecast VMT growth for heavy-duty vehicles reflects a close relationship between heavy-vehicle VMT and economic output (GDP or gross domestic product).

For the National Bridge Investment Analysis System (NBIAS), these forecasts build off bridge-level forecasts of future average daily traffic that states provide in the NBI. The sum of the bridge-level forecasts yielded an aggregate growth rate of 1.46 percent per year; growth rates for individual bridges were adjusted downward to match the 1.04 percent control total from the national-level VMT forecast model referenced above.

An underlying assumption applied in both HERS and NBIAS is that VMT will grow linearly (so that 1/20th of the additional VMT is added each year), rather than geometrically (i.e., at a constant annual rate). With linear growth, the annual rate of growth gradually declines over the forecast period.

New National VMT Forecasting Model[b]

The Volpe National Transportation Systems Center developed the National Vehicle Miles Traveled Projection for FHWA. The documentation for the model version used for this forecast is posted at http://www.fhwa.dot.gov/policyinformation/tables/vmt/vmt_model_dev.cfm. The current plan is to release revised national-level forecasts each May; this 2015 C&P Report relies on the 20-year national forecasts for the Baseline Economic Outlook from the May 2015 release.

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[a] FHWA and FTA 2016, 7–4.
[b] FHWA and FTA 2016, 9–6.

BOX C-8
VMT Forecasting Methodologies and Forecasts

Volpe Model and FHWA Forecasts
Pickrell et al. (2014) developed a set of three models for FHWA to forecast future changes in nationwide VMT for each of three vehicle types: light-duty passenger vehicles, light-duty trucks, and combination trucks. These models were specified on the basis of economic theories and developed with time-series data beginning in 1966. VMT by light-duty vehicles is a function of personal disposable income per capita, fuel cost per mile, and consumer confidence. VMT by light-duty trucks is a function of consumer spending, residential construction activity, and fuel cost per mile. VMT by combination trucks is a function of GDP, fuel cost per mile, and Interstate centerline miles. Since 2014, FHWA has used these models annually to forecast nationwide VMT for a 30-year horizon. Its 2015 version, the forecasts were used as control totals in summing up state-provided VMT forecasts for DOT's 2015 *Conditions and Performance Report* (FHWA and FTA 2016). FHWA relies on IHS Inc.'s spring release of the long-term economic outlook for the United States as input data for forecasting VMT. In its 2016 version for the baseline economic growth outlook (medium economic condition), FHWA forecasts an annual average growth rate of 0.47 percent for light-duty vehicles, 1.50 percent for single-unit trucks, and 1.87 percent for combination trucks, and 0.61 percent for all vehicles combined during 2014–2044 (FHWA 2016a).

DOE Model and Forecasts
As part of developing its annual energy outlook, the transportation module of DOE's National Energy Modeling System also uses a modular system of VMT forecasting (EIA 2016). At the highest level, it consists of the Light-Duty Vehicle Fleet submodule and the Freight Transportation Submodule.

- Personal travel—projects VMT per licensed driver as exponential regression function of fuel cost, disposable personal income per capita, employment rate for 16+, light-duty vehicles per licensed driver, and past VMT trends.
- Light-duty fleet vehicles—expands annual VMT per vehicle by vehicle type (cars or light trucks) and fleet type (private, government, or utility) with vehicle stock by vehicle, fleet, and engine technology fuel type (16 types).
- Travel by light commercial trucks (gross vehicle weight = 6,001–10,000 lb)—projects VMT per truck by growing 1995 base value on relative annual growth rates between industry sector output and light commercial truck VMT.
- Freight truck VMT—expands base year VMT per truck by number of trucks with additional adjustment.

For its *Annual Energy Outlook* 2017 (EIA 2017), DOE projects an average annual growth rate of 0.70 percent for personal and light-duty fleet travel, 1.50 percent for light commercial truck travel, and 1.3 percent for freight truck travel during 2015–2050.

Guidance Regarding VMT Growth for Future Interstate Initiative Policy Consideration

Based on the body of information presented, a number of observations relevant to policy planning activities for future Interstate Highway System transportation investment can be gleaned:

1. It is clear that the current and anticipated future conditions create a significantly large amount of uncertainty regarding future travel demand and system capacity. Forecasters have struggled to anticipate significant changes in factors that influence VMT, such as technology changes, economic conditions, and demographic trends, and the fundamental relationship between some of these conditions and travel levels is not sufficiently well understood to be the basis for highly confident future forecasts.
2. Although demographic shifts, economic cycles, and volatile fuel prices have long influenced VMT trends, the impact of technology changes and their potential to transform the business models for delivering transportation and alter travel needs by virtue of communication substituting for travel exacerbate the challenges of anticipating future VMT trends.
3. The presence of high uncertainty favors a strategy of considering various scenarios of future demand as an input for future transportation policy. The use of scenarios allows one to test the robustness of policy and investment initiatives to have intended consequences in light of possible different futures.
4. Existing quantitative models coupled with reviews of empirical trends provide an appropriate basis for testing the sensitivity of differing assumptions about the future. At the aggregate national level, VMT increases over the next two decades can reasonably be expected to range from the rate of growth of population (approximately 0.7 percent per year) to a rate of 2.0 percent per year if modest economic growth is assumed. Sustained rates outside that range would be expected only if there are pronounced changes in the economy. Beyond 20 years, maturation and market penetration of self-driving vehicle technologies might suggest different rates of long-term growth in VMT and different assumptions regarding roadway capacities.
5. Although it might be desirable to have robust long-term forecasts in light of the length of time to plan and implement Interstate System capacity improvements, the practical reality is that the backlog of investment needs and costs and the impact constraints on building capacity for potential long-term needs, coupled with

uncertainty regarding future lane throughput capabilities, diminish the criticality of long-term needs as a prerequisite for investment decisions. Seldom are we building new capacity on our roadway systems for future demand; most often, we are constrained to build capacity for prior or current levels of demand that are not being adequately accommodated today.

6. VMT scenarios can inform discussion about future Interstate System capacity requirements; however, financial and policy decisions, many made locally, will inevitably govern actual capacity expansion. The criticality of precision in VMT forecasts is muted by the fact that the Interstate System is part of a broader network of transportation facilities and services in which the consequences of failing to expand capacity are spread over a broader network.
7. Aggregate analyses at the national level are inherently different from those that consider specific facilities. In the case of the latter, more granularity is not only possible but critical. As noted above, the demand for Interstate System capacity is likely to be concentrated on a relatively small share of the total system, and the total new demands will comprise demand associated with population and travel growth as well as that attributable to population redistribution. Thus, the percentage increase in additional capacity to maintain performance will be larger than the average percentage increase in roadway volumes.
8. Current trends suggest that demand growth will be concentrated in growing urban areas—areas in which there is significant latent demand for high-performance roadway travel, and, as such, new capacity will attract and induce significant volumes. Urban Interstate highways interact and compete with other urban roadway and public transportation services and, as such, the consequence of increased demand will affect other elements of the transportation system and be affected by changes in those systems. Unless there is more active management and pricing of Interstate travel, urban Interstate System performance will be captive to overall corridor performance as travel demand shifts to the highest-performance travel paths. Similarly, urban Interstate performance is somewhat captive to local and state investments in other transportation facilities and services in the respective corridors. Urban Interstates, particularly for large and growing urban areas, capture significant local travel and thus struggle to preserve their intended mission and functional classification.
9. Urban Interstate capacity expansion is the most complex and expensive context for capacity expansion. In urban environments, policy considerations associated with the social, environmental,

and financial implications of capacity expansion will create huge challenges and place a premium on capacity expansion strategies that can be deployed within existing facility footprints.

10. The collective consequence of the various phenomena noted above create a context in which an annual <1 percent increase in population and 2 percent increase in GDP might create a 2 percent increase in VMT, which might create a need for a 3 percent increase in Interstate Highway System capacity, which might require a 5 or more percent increment in Interstate infrastructure asset value to sustain Interstate System performance. Thus, the aggregate increase in VMT underrepresents the infrastructure investment requirements for the system's performance to be sustained, given the geographic location of demand growth and the financial and policy implications of expanding capacity in areas where new capacity is most critical to sustain the system's performance. The investment requirements will be even higher if the cost of consensus results in low-priority investments working their way into the program of improvements.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
BEA	Bureau of Economic Analysis
BTS	Bureau of Transportation Statistics
EIA	Energy Information Administration
FHWA	Federal Highway Administration
FTA	Federal Transit Administration

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Appendix D

Economic Outlook Factors Affecting Highway Demand

Mark Sieber and Glen Weisbrod[1]

BACKGROUND AND OVERVIEW

Background

The Interstate Highway System is the backbone of the U.S. road network. It carries 25 percent of the total vehicle-miles traveled (VMT) and almost 40 percent of the truck traffic in the United States. Recognizing that the core system design dates back more than 60 years, Congress in 2015 authorized funding for a study of actions needed to upgrade and restore the Interstate Highway System to meet the increasing and changing demands of the 21st century.

This is one in a series of white papers commissioned as part of that study. It builds on two other papers developed for the study. One highlighted the key role of the Interstate Highway System in supporting freight movements and showed national forecasts of future freight growth. A second white paper examined the national trend in traffic growth, measured as VMT, and its relationship to growth in population, economy (gross domestic product [GDP]), and land use density (Polzin [see Appendix C to this report]). This appendix examines more specifically how future highway demand will be increasingly affected by evolving shifts in the economy.

[1] With assistance from Derek Cutler and Cecilia Viggiano.

Overview

The objective of this appendix is to show how economic changes affect demand for Interstate Highway System travel, the range of ways that economic changes can evolve, and the implications for truck and car highway demand (including VMT patterns). Four specific elements are examined:

1. *Economic factors:* It shows how freight and passenger travel demand patterns are shifting in response to temporal, spatial, and sectoral changes in U.S. business and population activity patterns, as well as evolving technology shifts that are affecting industry productivity, buying and selling, and transportation patterns. These factors are changing economic activity locations as well as freight and passenger traffic patterns.
2. *Trend effects:* It utilizes a long-term history, and a series of alternative long-term economic forecasts to show how the above-cited shifts in spatial, sectoral, and productivity characteristics of the economy have affected past, and will affect future, Interstate Highway System freight and passenger travel demand (including VMT patterns and trends).
3. *Economic outlook alternatives:* It portrays economic outlook forecasts reflecting alternative assumptions about changes in future economic drivers such as fuel prices, trade, and economic productivity. It uses the alternative forecasts to illustrate uncertainty factors, and their range of possible impacts on future Interstate Highway System travel demand.
4. *Interpretation:* It provides a context for interpreting how alternative economic futures can affect the range of future Interstate Highway System travel needs and their sensitivity to future uncertainties. This will also provide a basis for subsequent use of the information to assess the potential for over- or underinvestment and their implications.

This appendix presents forecasts of changes over 10-, 20-, 30-, and 50-year time periods. However, for clarity, it utilizes the 30-year forecasts to drill down and show how various economic change factors are evolving to affect future highway demand and investment needs.

How the Economy Drives Highway Demand Patterns

There are many ways of viewing the growth of highway demand. Since the Interstate Highway System was authorized 60 years ago, the U.S.

population has grown 74 percent. Over this same period, the number of registered automobiles has increased 239 percent. Over the past 30 years alone (1985–2015), overall highway traffic (as measured by VMT) has grown 74 percent. Importantly, the various factors underlying the growth of highway travel demand (e.g., population, income, car ownership, and truck movements) are all driven by the same set of core changes over time in the pattern of economic activity.

Behavioral Relationships

We can see these relationships by considering the schematic in Figure D-1 and the corresponding concepts of economic base and economic geography that explain compositional and locational shifts in economic activity among regions and their consequences. (In this nomenclature, a region can be a county, a metro area, or a state.)

The core drivers of the economy are basic or traded industries, that is, industries that locate where it is most feasible and profitable to do so because their products can be sold nationally or internationally. (This includes most mining, agricultural, forestry, manufacturing, technology services, and supply chain activities). Over time, the size, composition, and location patterns of these industries shift among regions, and so do the corresponding job and income opportunities. Population growth follows the changes in basic job opportunities, and other population-serving industries (education, health care, retail stores, and personal services) follow population movements.

There are changes in truck and car generation rates, locations, distances, and overall VMT that result from these changes in economic activity and their related shifts in job and population patterns.

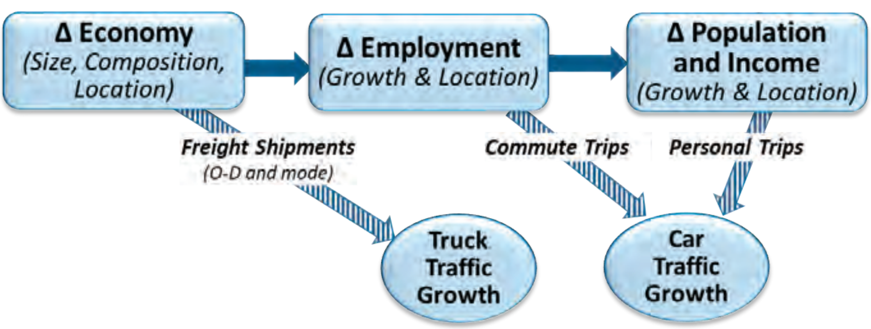

FIGURE D-1 How changes in the economy affect car and truck VMT.
NOTE: O-D = origin-destination.

Traffic Consequences

The evolution of economic activity over time can be viewed in terms of changes in regional economic *growth* and *composition (specialization)*. This has the following consequences:

1. Economic growth affects employment. More employment means more commuter trips.
2. Economic growth generally leads to higher income, increasing consumption of goods and thus also demand for freight transportation. More income also increases demand for personal and recreation and tourism travel, and purchases of automobiles.
3. Shifts in regional economic specialization reflect the division of labor, both internationally and spatially within the United States. A more advanced division of labor can mean more regional economic specialization, shifting the location of economic activity (traded industries), the types of products being produced and shipped, and their origin–destination pattern. This also leads to shifts in freight mode split as well as the location and length of truck trips. More trade, with longer shipments, generally means more truck traffic on the Interstate Highway System.
4. Shifts in the location of traded industries also lead to location shifts in population patterns and population-serving industries. That, in turn, drives further growth in traffic on highways within the affected regions.

Bottom Line

While economic growth drives overall traffic (VMT) growth, it also leads to critical changes in the location of generated highway traffic, car and truck mix of traffic growth, and trip distance and origin–destination pattern of that traffic. This can have profound implications for the future adequacy of the Interstate Highway System network and affect investment priorities.

Organization of This Appendix

The next section shows how economic change has been affecting these various aspects of highway demand. The third section then explores the implications for the baseline future and demonstrates the range of alternative economic futures. Failure to anticipate possible future scenarios can lead to potentially either "stranding" overinvestments in highways or failing to adequately invest in future highway needs.

HOW THE ECONOMY HAS INFLUENCED TRAVEL DEMAND TO DATE

This section examines past trends and current patterns concerning the relationship of highway demand and economic growth. By examining this issue, we can identify factors that will also be relevant for forecasting future highway needs (later in the section on what we can expect).

Aggregate VMT Growth Hides Shifting Factors

Aggregate Trends

There has been a continuing long-term trend in which VMT has grown, along with the growth of economic activity (GDP), employment, population, and income. Figure D-2 shows how the growth trend for national VMT compares to the growth trend for national GDP over 84 years.

Similar graphs can be made by relating VMT to growth in population or total household income. However, these aggregate trends mask a number of important shifts that offset each other when looking at overall national statistics but become critically important when viewing localized highway needs. They include the following:

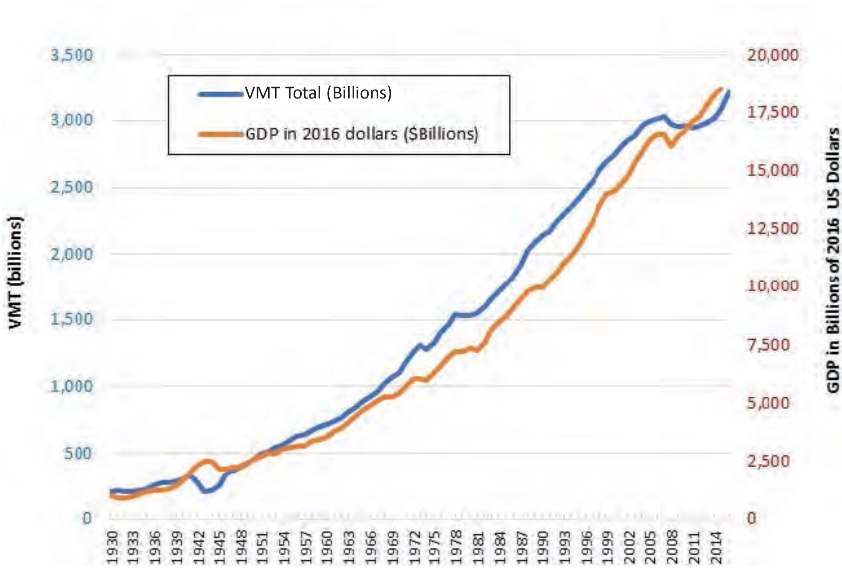

FIGURE D-2 National VMT and GDP trends.
SOURCE: FHWA 2017, Table VM-202.

- Changes in the spatial pattern of workforce participation patterns over time;
- Changes in the relative levels of worker income and their spatial pattern over time;
- Changes in the regional location pattern of VMT growth on highway networks;
- Changes in the car/truck ratio on highways;
- Changes in the origin, destination, and distance characteristics of car and truck trips, reflecting both longer supply chains nationally and longer commute patterns in major, growing metro areas;
- Changes in the share of truck movement going to and from air, sea, or rail terminals or land borders; and
- Changes in the types of freight carried by trucks and their service to supply chains and distribution centers (which reflects evolution to lean manufacturing and integrated supply chain technologies, building on IT/telecommunication advances and vertical integration).

These factors have had offsetting impacts on the observed national-level traffic and economic trends that were previously shown in Figure D-2:

- Some of these factors *decrease* VMT growth. They include growth over time in air and sometimes also rail alternatives to highway travel, which are applicable for some intercity freight and passenger movements. They can also include improvements in truck utilization (fewer empty backhauls) for some industries.
- Some of these factors *increase* VMT growth. They include rising income levels, growth of international trade, longer supply chains, more international trade, and the spatial expansion of large labor markets over time.
- Some of these factors *shift the location* of VMT growth, but not necessarily change its rate nationally. They include changes in manufacturing and supply chain locations, and consolidation of distribution centers.

So, in the end, the total level of VMT may appear to have grown in step with the economy's long-term growth, but there have also been important shifts in the location and composition of traffic, which have affected total traffic levels on different parts of the highway system. These same types of trends continue to occur and will be important as we consider expectations for future traffic growth and future highway investment needs. For instance, Figure D-3 shows that truck VMT have been growing faster than passenger car VMT. And of course, trucks have a much larger impact on

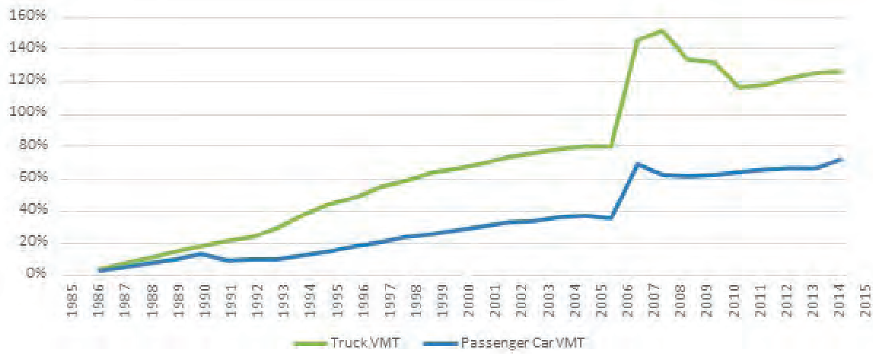

FIGURE D-3 Truck and passenger car VMT growth, 1985–2015.
NOTE: There was a redefinition of vehicle types in 2007, followed by the economic crisis from 2008 onward, which explains the rapid changes around these years.
SOURCE: BTS 2017a, Table 1-35.

road capacity utilization and degradation than cars. Next, we examine how VMT composition and location patterns are also changing.

Location of Economic Activity and Its Composition Is Shifting Intercity Highway Needs

Concentration of Economic Growth

The location of economic activities occurring in the U.S. economy has been shifting significantly over time, and that is changing the pattern of highway use for freight and passenger travel. High-growth industries such as wholesale trade and computer and electronic manufacturing are concentrated in a few parts of the United States, particularly in the megaregions of the Southeast and Southwest, with pockets in Northeast and Northwest metro areas. One of the indicators for the location of economic activities is the spatial distribution of jobs. Jobs lead directly to commuting trips, of which 86 percent are by cars as drivers or passengers (BTS 2017b). Jobs are also an indicator for supply and demand of shipped goods for traded industries. About two-thirds of all freight tons are carried by trucks (FHWA and BTS 2013).

The spatial pattern of employment growth follows shifts in key growth industries. Figure D-4 shows the spatial pattern of overall jobs by county as of 1985. Figure D-5 then shows how that spatial pattern has since shifted from 1985 to 2015, reflecting systematic losses in some parts of the country and increased gains in others.

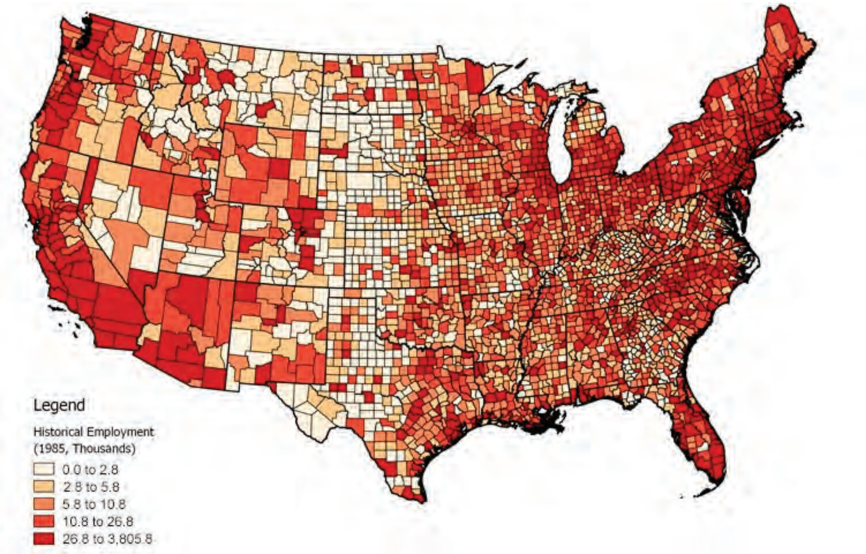

FIGURE D-4 Employment 1985, by county.

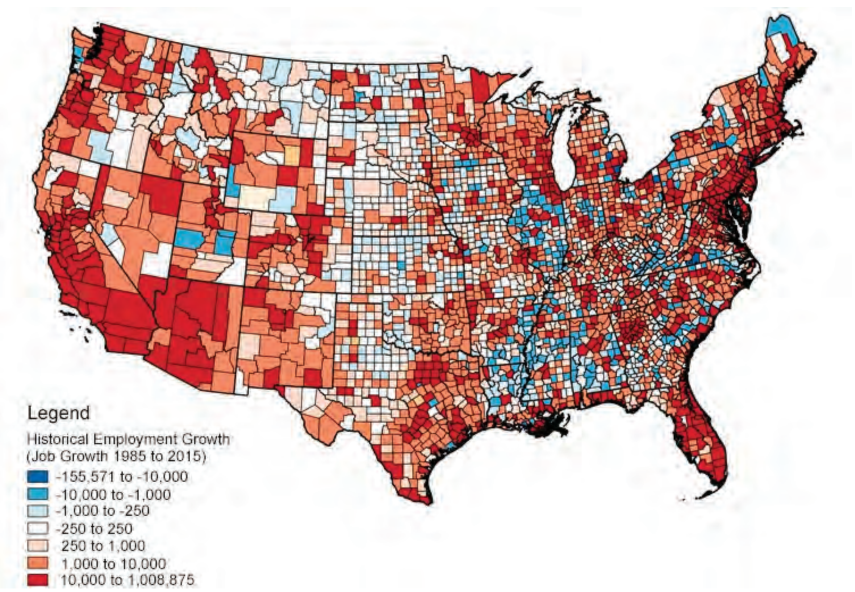

FIGURE D-5 Change in employment, 1985–2015, by county.

Key Differences in Highway Reliance Among Industries

There are systematic and large differences among industries in terms of the extent to which they generate truck traffic (VMT). We can break down the factors driving truck traffic growth into three components: freight trip generation rates, truck reliance rates, and trip lengths, all of which vary systematically among industry. These differences among industries are shown in Table D-1. While there is also some variation in these rates over time in these statistics, they are small compared with the fundamental differences among industry sectors. This is a critical point, for the mix of economic activities occurring in the U.S. economy has been shifting significantly over time, and that is changing the pattern of highway use for freight travel.

Consequences of Industry Growth and Decline Patterns for Traffic Growth

As the economy evolves, there are changes in the industry mix of economic activity. The evolving shifts in economic activity combine with the above-cited differences in truck traffic generation, to affect highway freight flows in the United States. This shows up in various ways:

- Industry products with high freight tonnage and relatively low value per ton, such as petroleum, coal, mining and mineral products, chemicals, and primary metals have less of an impact on highway demand because much of their typical shipment distance is by rail.
- On the other hand, output of high computer and electronic technology products has grown domestically. Their high value and weight, continued growth, and global nature of their markets all support increased use of air freight, which also generates regional truck distribution shipments among airports, regional distribution centers, and customers. Ultimately, this still grows truck traffic but shifts its origin–destination pattern.
- Apparel, leather, and computer and miscellaneous consumer goods are increasingly being delivered to massive centralized warehouses by large trucks and then delivered to households via light trucks operating within metropolitan areas. This phenomenon has concentrated truck cargo movements in metropolitan areas.
- Effects of regional economic specialization lead to the concentration and consolidation of industries in specific regions. The locations of these producer concentrations have shifted with the ongoing trend toward more technology-based industries and products.
- As service industries have grown, so has the volume of metropolitan truck deliveries—a market segment that is not well captured by current freight shipment statistics.

TABLE D-1 Differences in Tonnage, Truck Reliance, and Shipment Lengths, by Industry

Industry	Tonnage (millions)	Tons per Employee	By Truck (%)	By Multiple Modes* (%)	Miles per Shipment	Value per Ton ($1,000s)
Crop production	1,493	992.5	80.6	2.4	637.3	357
Animal production	237	202.7	91.7	1.6	715.6	1,060
Forestry and logging	337	2,321.1	91.3	0.1	1,521.2	49
Fishing, etc.	6	58.0	93.2	1.9	366.1	1,349
Oil and gas extraction	778	956.9	29.2	0.5	77.5	721
Mining, quarrying, and support	4,133	5,379.6	61.7	2.6	353.7	74
Food manufacturing	985	545.1	88.5	2.6	545.9	1,125
Beverage and tobacco product manufacturing	185	747.1	90.5	3.1	315.0	1,658
Textile mills and products manufacturing	33	134.4	88.8	6.7	268.2	8,569
Apparel manufacturing	10	58.0	89.0	9.2	340.6	12,996
Leather product manufacturing	4	105.4	87.3	11.6	613.1	12,594
Wood product manufacturing	430	962.5	89.5	3.1	787.4	574
Paper manufacturing	246	653.2	82.5	3.4	808.2	982
Printing	18	32.0	92.0	6.7	406.5	4,190
Petroleum and coal products manufacturing	3,845	33,362.4	34.1	0.6	179.4	596
Chemical manufacturing	761	963.7	61.8	2.9	331.6	2,390
Plastics and rubber products manufacturing	107	151.8	78.4	4.3	649.2	3,252
Nonmetal mineral product manufacturing	1,029	2,403.3	92.0	1.7	488.7	205

TABLE D-1 Continued

Industry	Tonnage (millions)	Tons per Employee	By Truck (%)	By Multiple Modes* (%)	Miles per Shipment	Value per Ton ($1,000s)
Primary metal manufacturing	375	924.0	79.8	3.9	731.9	1,218
Fabricated metal manufacturing	235	155.3	89.4	3.1	543.4	2,409
Machinery manufacturing	123	107.8	91.9	3.3	2,181.7	5,958
Computer and electronics manufacturing	53	54.3	87.8	8.9	333.1	19,062
Electrical equipment and appliance manufacturing	40	99.1	92.1	4.6	785.6	10,803
Transportation equipment manufacturing	270	167.6	85.0	5.1	381.2	5,461
Furniture manufacturing	55	130.5	95.8	1.6	408.6	4,903
Miscellaneous manufacturing	72	106.2	88.5	6.8	274.5	7,835
Wholesale trade	384	59.6	96.3	1.5	431.8	3,644
Media and information	19	5.5	92.3	6.2	361.0	4,111
Business services	248	20.7	92.6	1.7	517.3	123

*Multiple modes include truck–rail, truck–air, and truck–marine shipments.
SOURCE: U.S. Census Bureau 2007.

The combination of all these effects leads to shifts in the *freight intensity* of industries in different areas of the country. Freight intensity is defined here as the tonnage of incoming and outgoing freight per employee, relative to the national average. Figure D-6 shows the relative freight intensity of counties as of 1985, which reflects differences in the mix of industries located in various areas. Figure D-7 shows how freight intensities have grown or fallen between 1985 and 2015, which also reflects the change in industry mix at those locations. The relative freight intensity ratio has been highest in traditionally industrialized areas such as parts of Michigan and Ohio. However, it decreased in many of those areas between 1985 and 2015. Meanwhile, other counties' industry mixes have grown more freight-intensive relative to the national average. The measure used to represent freight intensity is explained in the first section of the Addendum.

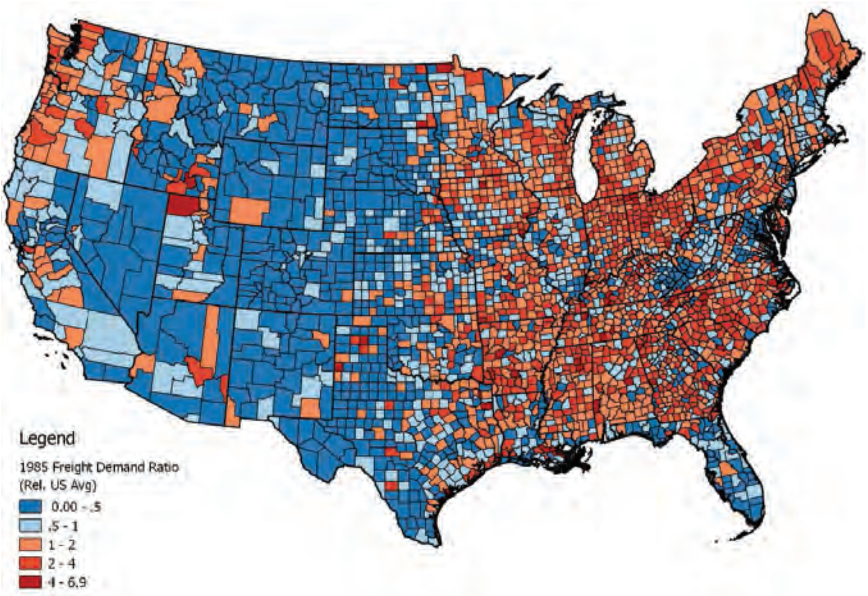

FIGURE D-6 Freight demand intensity relative to U.S. average, 1985, by county.

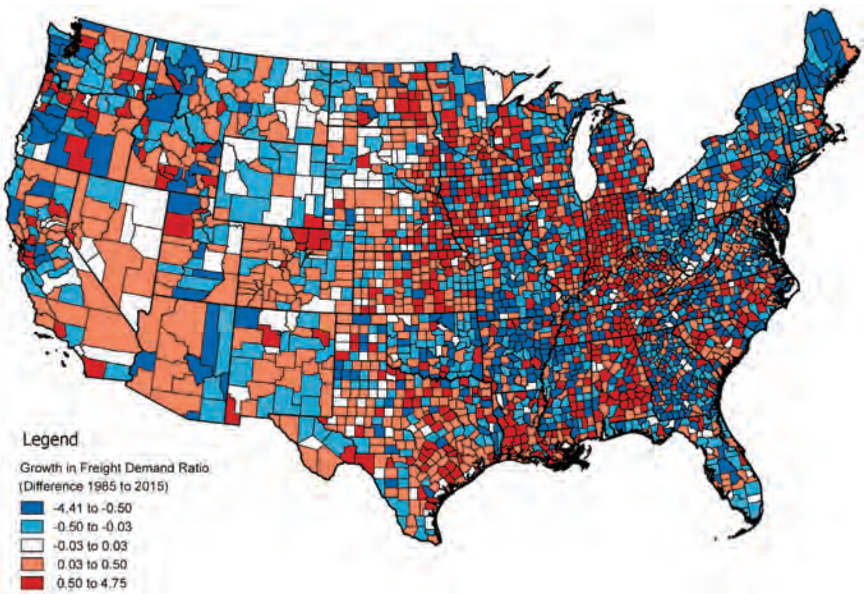

FIGURE D-7 Change of freight demand intensity relative to U.S. average, 1985–2015, by county.

Urban Population Patterns Follow the Economy and Shift Metropolitan Highway Needs

The spatial pattern of population growth over 30 years is shown in Figure D-8. The pattern generally mimics the spatial pattern of employment growth over the same period, which was shown as Figure D-5, even though there are few areas with an absolute decrease of population numbers. Population movements have tended to follow job creation because workers tend to move to where the jobs are.

The key point to note is that past population growth has been largely concentrated in a relatively small number of metropolitan areas. Population losses are apparent for rural areas of Maine, parts of the Appalachian region, and the Mississippi River Valley. This trend means that some areas will have reductions in passenger car traffic on highways, whereas others will have disproportionately higher than average growth in local highway demand.

Estimates of passenger VMT demand are derived using the Bureau of Transportation Statistics 2009 National Household Travel Survey (NHTS)

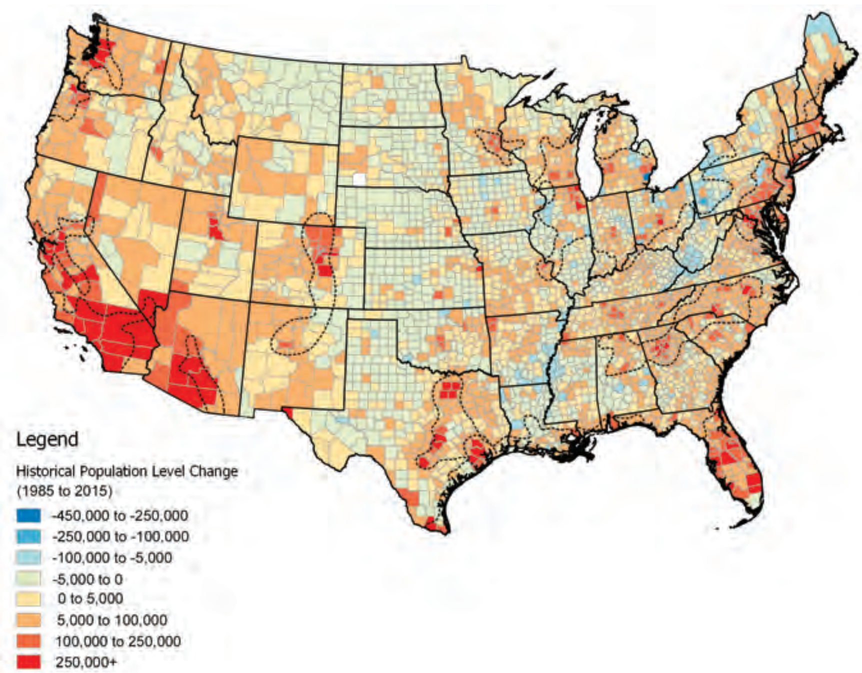

FIGURE D-8 Population growth, by county, 1985–2015 (showing shapes of megaregions).

Transferability Statistics research (Manson et al. 2017).[2] The change in VMT generation rate, expressed as VMT per household, is shown in Figure D-9 for the period between 1990[3] and 2015. The map shows a dispersed pattern with a tendency to decreasing VMT per household in the East and West, and increasing in the Midwest.

The variation in VMT generation rate among regions affects the use of highways, which is the reason why this is yet another factor to be considered when estimating future volumes on the Interstate Highway System. Daily VMT per household depends mainly on the household size, the number of workforce participants per household, and the level of income. The areas with a rising VMT generation rate appear to roughly correspond to

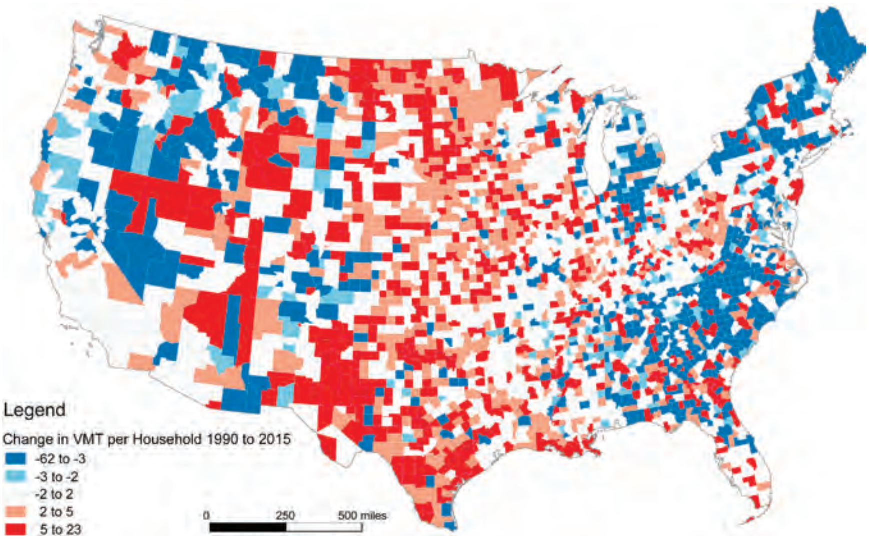

FIGURE D-9 Growth in ratio of daily passenger car VMT per household, by county, 1990–2015 (estimates).

[2] This research provides regression coefficients for estimating household trip-making and VMT based on sociodemographic characteristics. Separate regressions are available for regions of the country and the urban, suburban, and rural portions of each region. The Transferability Statistics classification of urban, suburban, and rural areas is made at the Census tract level based on urbanization and population density. This was calculated for both 1990 and 2015. Counties were assigned classifications by summing population across tracts and assigning the county the dominant classification. For the 2015 baseline, county-level estimates are based on the 2011–2015 American Community Survey. The variables of interest were also acquired from the 1990 decennial Census through the National Historical Geographic Information System (Manson et al. 2017).

[3] Data for 1985 are not available, but would have to be generated as a mean between 1980 and 1990.

areas of stagnant employment shown earlier in Figure D-5. This trend may reflect lower income growth and/or more workers per household, though further work will be necessary to confirm these relationships.

Growth in total daily passenger car VMT can be computed by considering the VMT per household ratio together with growth in the number of households in each county. Figure D-10 shows estimates of this metric in terms of its spatial distribution. In large parts of the United States, daily VMT increased considerably between 1990 and 2015. Decreasing or stagnating areas may be found for instance in the Midwest and along the Mississippi River. This map is particularly useful in illustrating locations where car VMT growth is occurring. It may also be interesting in the future to consider rates of VMT per square mile.

Bottom Line

As America's economy evolves over time, there are systematic changes in location and composition of economic activity. These systematic industry activity changes translate into substantial changes in the level and pattern of truck freight travel patterns as well as car traffic within metropolitan areas. The past and current relationships shown in this section provide a basis for estimating the impacts of economic future forecasts in the next section.

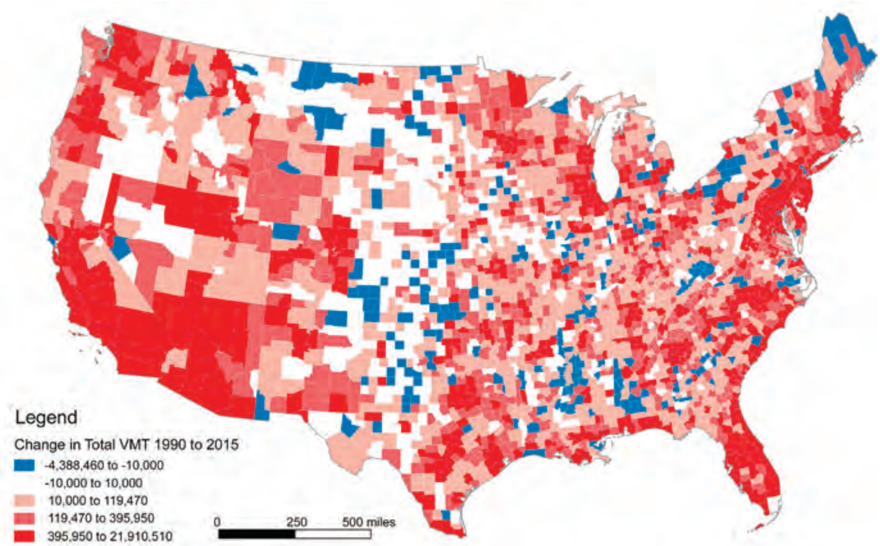

FIGURE D-10 Growth of total daily passenger car VMT, by county, 1990–2015 (estimates).

WHAT CAN WE EXPECT FOR THE FUTURE?

The information in the preceding section on how the economy affects highway traffic provides a basis for now considering expectations about the long-term future evolution of the U.S. economy and its implications for future highway traffic. This section is organized into three main parts.

1. It presents a baseline economic and demographic forecast for the United States and examines how it is expected to change future highway travel demand.
2. It then presents a series of alternative economic forecasts that reflect differing assumptions about energy and transport cost changes, international trade policies, and global economic growth. It then discusses the difference in highway travel impact associated with these alternative future forecasts.
3. Finally, it discusses additional scenarios and factors that can also affect the future economy and highway travel demand.

The analysis that is presented in this section focuses on 30-year forecasts for clarity and simplicity of discussion. However, the Addendum presents additional forecasts and analysis for shorter (10- and 20-year) time frames and a longer (50-year) time frame.

Baseline Economic Outlook and Highway Travel Consequences

Definition of Baseline

American industry relies on short-, medium-, and long-term models provided by private firms to forecast future demographic and economic changes. The two best-known firms are Moody's Analytics and IHS Markit (formerly Global Insight). In general, the two services provide similar forecasts. Although the Federal Highway Administration (FHWA) Office of Policy relies on IHS Markit for its VMT forecasts, the analysis in this appendix used Moody's to access detailed year-by-year forecasts of demographic shifts and industry sector shifts by detailed categories for every county in the United States covering a 30-year period. (The forecasts were later extrapolated to 50 years; see Addendum for details.) For reference purposes, Moody's baseline forecast shows 0.68 percent annual employment growth rate over 2015–2045, whereas the IHS Markit forecast shows 0.75 percent. The corresponding GDP annual growth rates are 1.87 percent for Moody's and 2.06 percent for IHS Markit. Thus, the two forecast sources track closely together, although the Moody's growth numbers are slightly lower.

Moody's data used for this study include highly detailed demographic and economic forecasts. The demographic forecasts included information on changes in population, households, household size, type, workforce, retirees, and children. The economic forecasts included information on GDP (value added), employment (jobs), and worker income generated for 53 industry sectors. All forecasts are disaggregated for each of more than 3,000 counties, for each year.

The source of the baseline demographic and economic forecasts was the Moody's U.S. macro model. It estimates how the economy, population, and workforce will shift in future years under explicit scenario assumptions such as slowly growing global markets, increasing productivity and stable cost-competitiveness, generally stable energy and other resource prices, stable international trade regulations, strengthening of the dollar against foreign currencies, slowly rising inflation and interest rates, and full employment growth that is not constrained by labor market size. Alternative assumptions are considered later, in the section on alternative economic futures.

In each case, the Moody's national macro model forecasts of economic growth are allocated to states and counties based on a second Moody's model that considers their relative competitiveness for attracting and growing each of the industry sectors. The TREDPLAN[4] analysis system was then applied to calculate and display further implications of alternative scenarios, including demographic and economic shifts for intercity flows of investment, income spending, people, and freight.

Baseline Economic Change and Highway Travel Implications

The forecast of 30-year change in employment by industry is represented in Figure D-11 for the largest industries. The expectation of overall 42.5 million additional jobs in 2045 (+23 percent) is the aggregation of 53 industries with major shifts in workforce demand among themselves. Specifically, the forecasts show higher than average growth will occur in 13 industries, which make up 60 percent of today's overall jobs; lower than average growth will occur in 40 industries.

Most of the industries with the highest growth are service industries, which follow the population shifts and therefore will be spread according to population distribution across the country. This part of growth changes will emphasize the concentration trend of people and jobs in metropolitan areas and, above all, in the nation's megaregions, where highway use will grow accordingly. This will raise planning challenges insofar as the megaregions transcend metro and state boundaries.

[4] See https://www.tredis.com/products/tredplan.

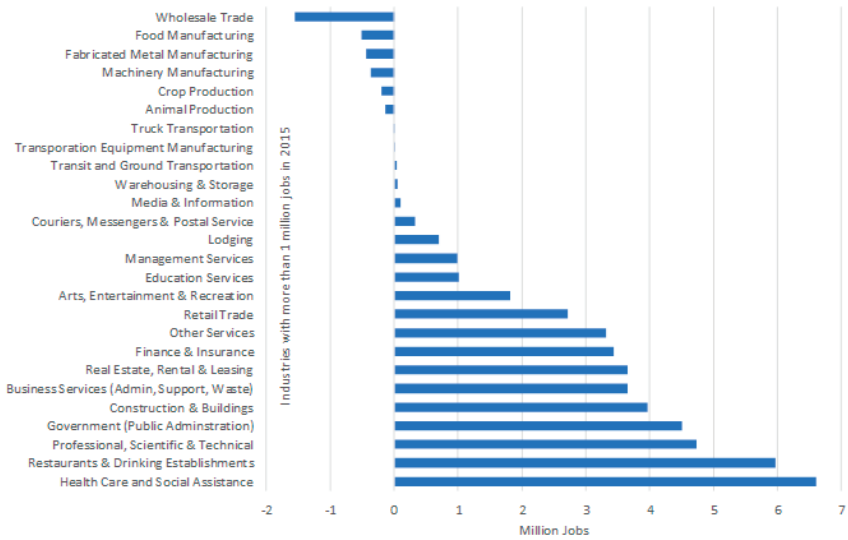

FIGURE D-11 Forecast change in national employment, by industry, 2015–2045.

Other industries show different spatial growth and decrease patterns, which do not necessarily correlate with population growth. These patterns are further explored for four example industries (see Figures D-12–D-15).

The trucking and warehousing and storage industries, which are mapped together in Figure D-12, are forecast to show an overall growth of 58,000 jobs over the next three decades. The additional jobs occur not only in metropolitan areas, but also in hotspots along major Interstate highways because highway accessibility is obviously crucial to this industry. Even though the absolute change in the number of jobs is modest, the freight-related nature of this industry makes its location important as a generator of traffic on Interstate highways.

The professional, scientific, and technical services industry (see Figure D-13) is projected to add 4.7 million jobs by 2045. Much of its growth is projected to occur in the megaregions, although there are also many counties outside of those areas that are expected to see job growth in this industry sector. Because of its size and its magnitude of change, the spatial pattern of this industry is important for future traffic volumes on Interstate highways. In particular the high labor intensity of this service industry increases the density of urban commuting trips. This can also put pressure on urban Interstate highways unless there is increased use of other modes.

The machinery manufacturing industry (see Figure D-14) is forecast to continue its decline in terms of domestic jobs in the United States. Between

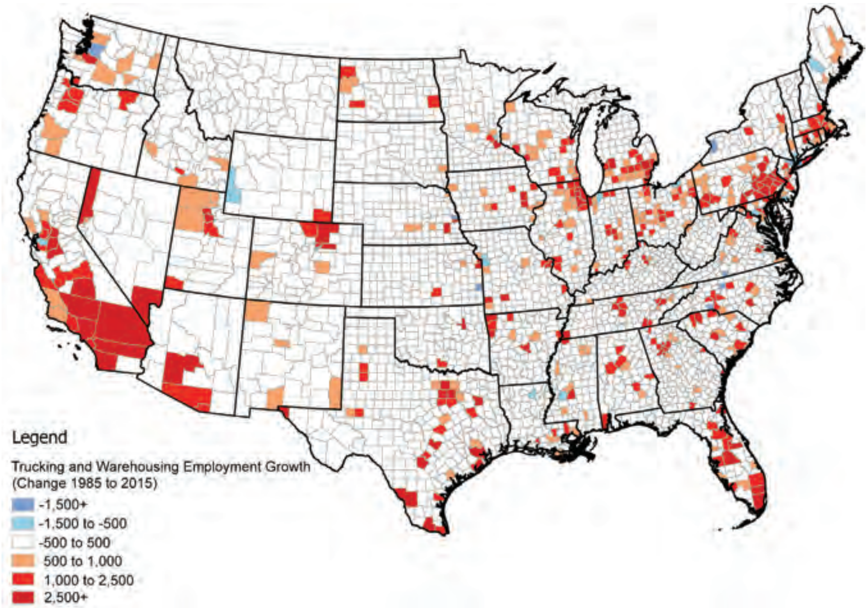

FIGURE D-12 Trucking and warehousing and storage: Spatial pattern of job growth and decrease, by county, 2015–2045.

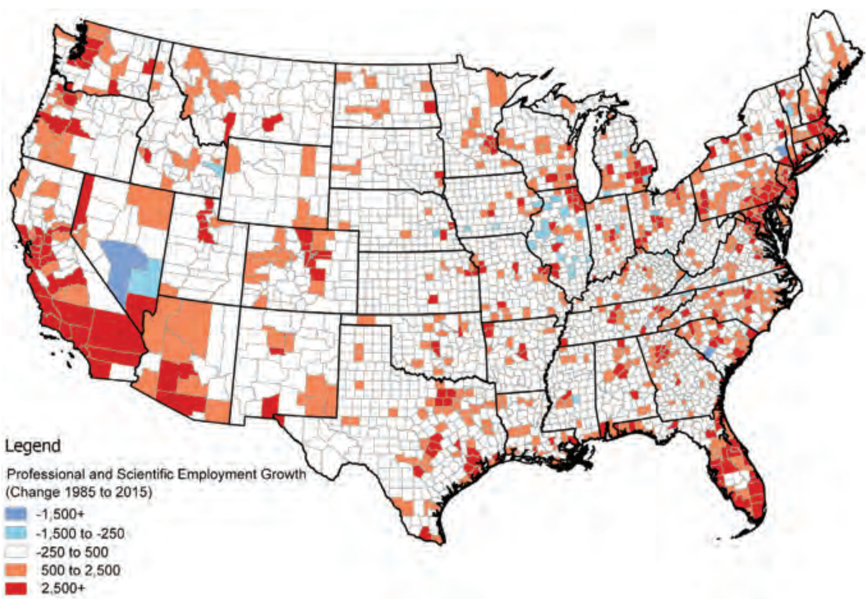

FIGURE D-13 Professional and scientific and technical: Spatial pattern of job growth and decrease, by county, 2015–2045.

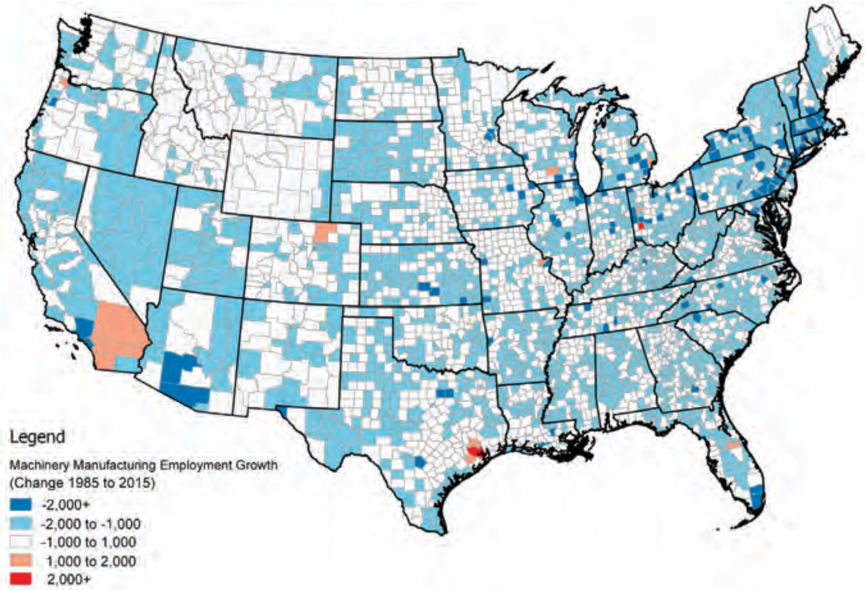

FIGURE D-14 Machinery manufacturing: Spatial pattern of job growth and decrease, by county, 2015–2045.

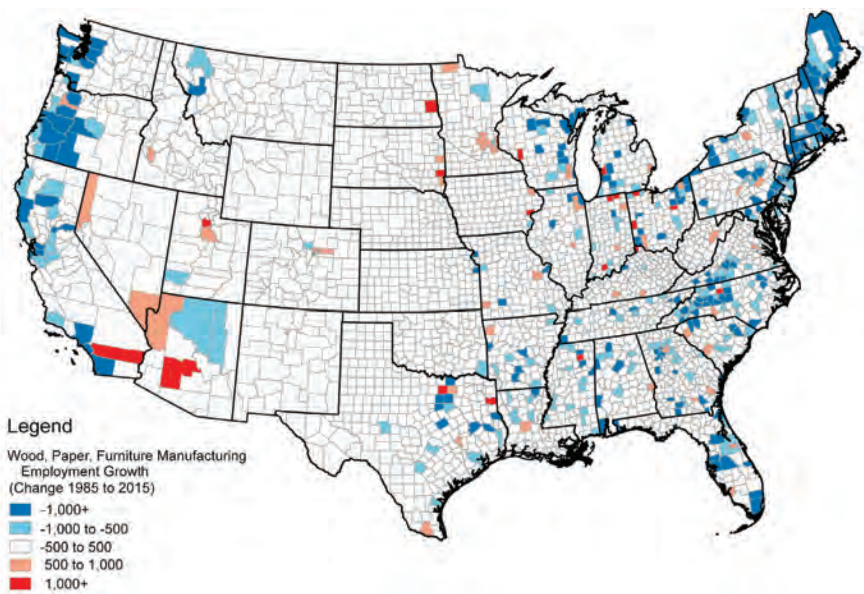

FIGURE D-15 Wood, paper, and furniture manufacturing: Spatial pattern of job growth and decrease, by county, 2015–2045.

2015 and 2045, it is forecast to lose 369,000 jobs. The analysis shows that this loss will be widely dispersed and not particularly concentrated in areas that have traditionally been manufacturing centers. The effect on highway travel will also be dispersed.

The wood, paper, and furniture manufacturing industries (see Figure D-15) are expected to lose about 250,000 jobs over the next 30 years. These decreases occur mostly in rural areas close to lumber sources. This pattern is highly concentrated and is projected to lead to slow population growth in many of the affected areas. This can reduce demand for Interstate highway travel to and from these areas, although that also depends on the extent of rail use. In some of the wooded areas, there is also rising tourism that can have an offsetting effect on area VMT.

Future shifts in the employment growth and decline in each county can lead to further substantial impacts on the overall spatial pattern of nationwide employment. This is shown in Figure D-16, which illustrates the Moody's Analytics model (baseline) forecast for 2015–2045 employment growth patterns. The spatial pattern of employment growth reflects a shift in growth rates among industries (see Addendum), and their interaction with differing state-level tax and related economic policies.

Shifts in freight mix will also be an important factor affecting freight use of Interstate highways. "Freight intensity" refers to the extent to which

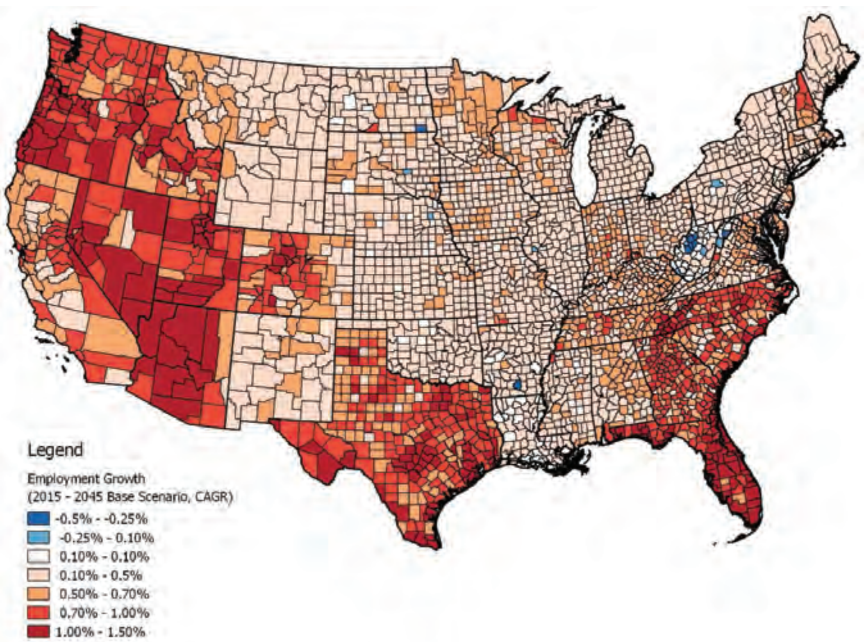

FIGURE D-16 Forecast change in employment, by county, 2015–2045.

economic activities require incoming freight shipments for their operations. There is a systematic variation in freight intensity associated with different industries (see Addendum Table D-A1). Since the local industry mix varies widely among areas, so does the freight intensity of economic activity. Figure D-17 shows the spatial pattern of change in freight intensity (relative to the U.S. average change) that is forecast to occur between 2015 and 2045. The forecast pattern indicates growing industrial and hence freight intensity in parts of the West, South, and Southeast/Mid-Atlantic regions. By adding assumptions regarding future truck and rail mix, it will also be possible to show the expected intensity of future truck cargo generation. Detailed information about the industry changes over time are provided in the Addendum.

Baseline Demographic Change and Highway Travel Implications

The baseline economic growth of traded industries is projected to also drive shifts in workforce and population location patterns, which will then also attract population-serving activities. Figure D-18 shows the expected impact on population growth patterns and the evolution of megaregions. Counties forecast to have higher than average growth include some areas

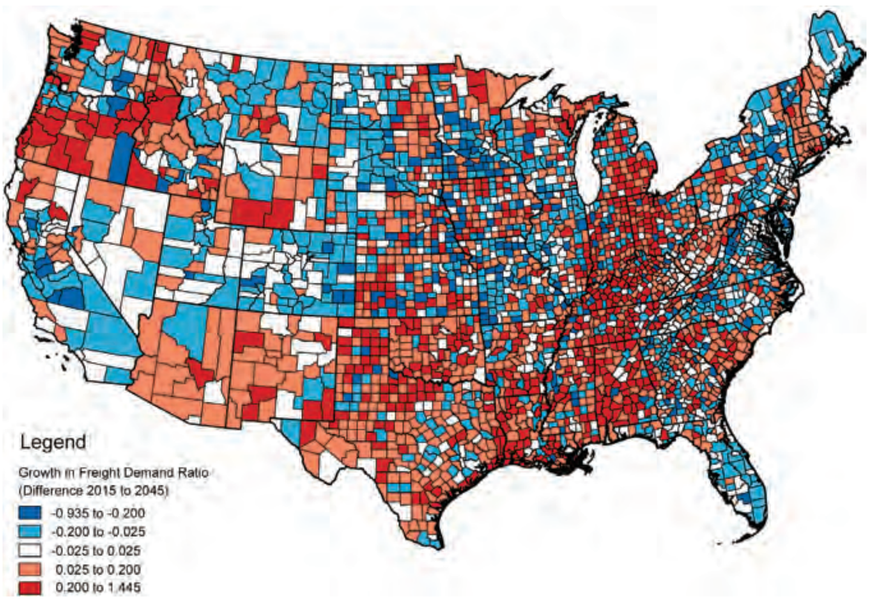

FIGURE D-17 Forecast change in freight intensity relative to U.S. average, by county, 2015–2045.
NOTE: More information about freight intensity is provided in the Addendum.

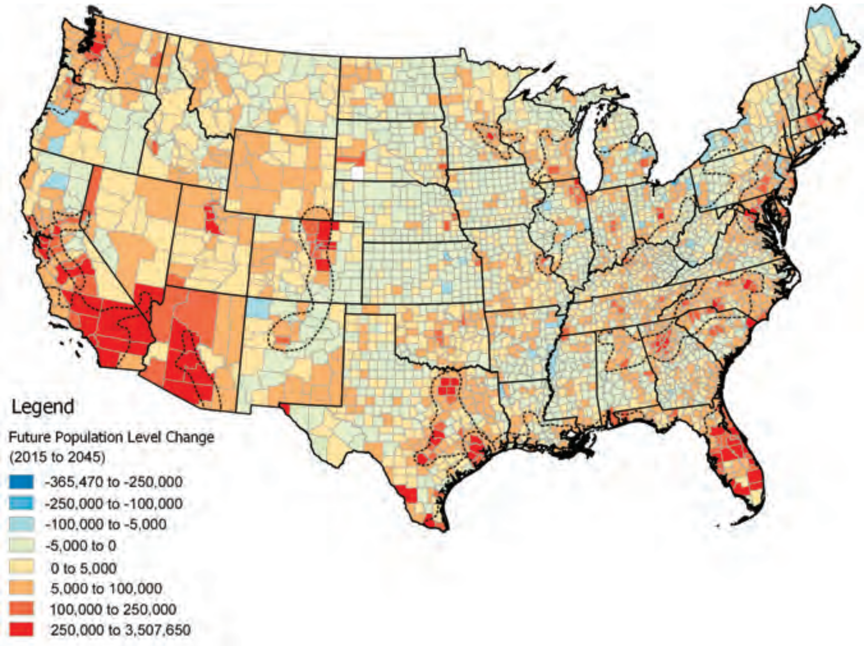

FIGURE D-18 Forecast change in population by county, 2015–2045 (showing shapes of megaregions).

that are already fast-growing, including Southern California, the Bay Area, the Texas Triangle, southern Florida, and some other metropolitan areas. These areas will also experience higher than average increases in commuting traffic on area highways, unless there are substantial efforts to shift more commuting to alternative modes. Where highways are already congested today, the future situation may be particularly challenging.

The study team applied forecast data presented in this report to forecasts of future VMT per household that were derived from Bureau of Transportation Statistics 2009 NHTS Transferability Statistics research. The results indicate that the ratio of VMT per household will grow mainly in the Midwest and the West (see Figure D-19). The highest growth rates appear in the dynamically changing areas in the Southwest. Growth in total passenger VMT (see Figure D-20) increases in the fast-growing megaregions, in the West, but also in the East and North. Most of the counties with decreasing or stagnating passenger VMT are part of the Midwest or the South. Reasons may be relative changes in the household size, in the workforce participation, or in the level of income.

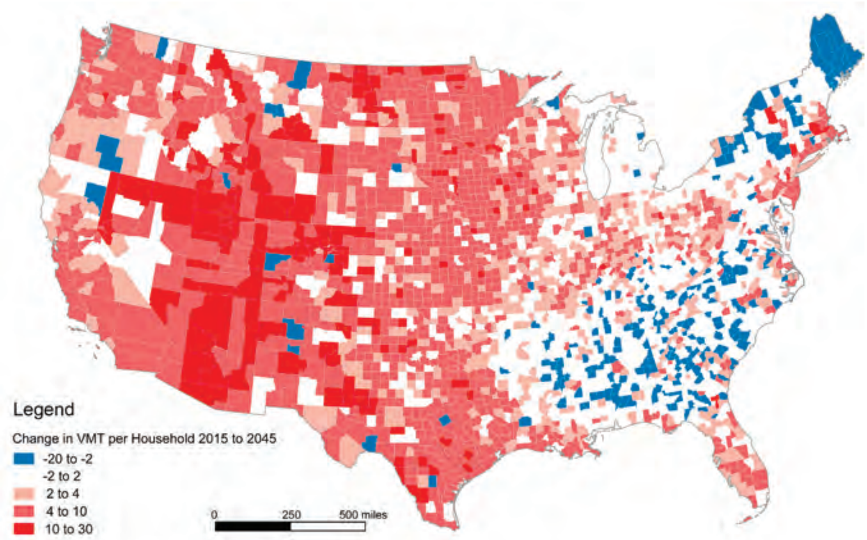

FIGURE D-19 Forecast growth in ratio of daily passenger VMT per household, 2015–2045.

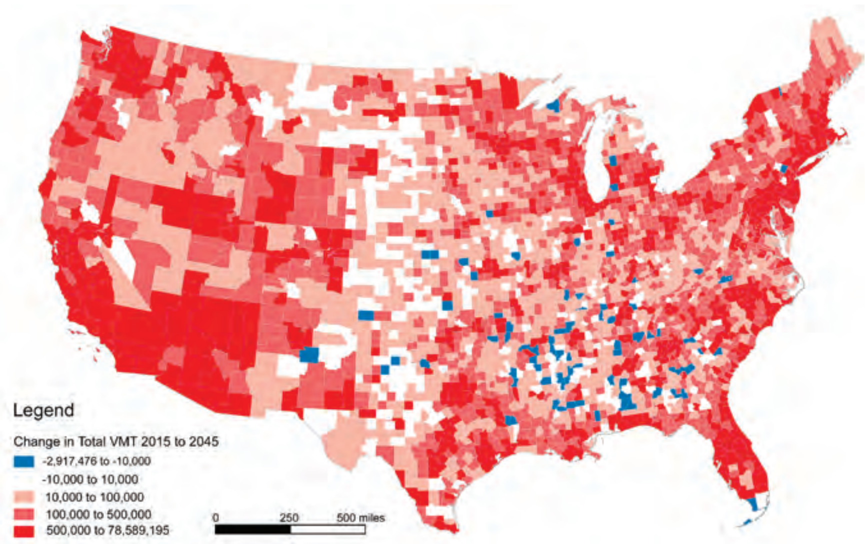

FIGURE D-20 Forecast growth in total daily passenger VMT, 2015–2045.

Alternative Economic Futures and Highway Travel Consequences

There is significant uncertainty about future economic changes, since there may be unforeseen factors that will affect the assumptions made about relative changes in U.S. productivity and cost-competitiveness, energy and other resource prices, international trade regulations, or other factors. This section explores implications of changing these assumptions. Other possible causes of future economic uncertainty, such as weather events, seismic events, or other unforeseen political or social disruption events, are discussed in an example later in the section on additional sources of future economic change.

For illustrative purposes, we consider three alternative futures and their implications for changing highway travel demand. They were selected from the eight alternative scenarios provided by Moody's Analytics (2017). The development of economic indicators for the scenarios is demonstrated in the Addendum.

The first two alternative futures represent extreme economic developments in one or the other way, while the third alternative has mixed outcomes:

1. *Stronger U.S. economic prosperity.*[5] Upside scenario of more positive global growth, increasing U.S. exports, greater nonresidential investment, and additional job growth of 1.8 million jobs by 2045.
2. *Protracted economic slump.*[6] Downside scenario of recession with falling stock market, lower bond prices, reduced trade and U.S. exports, higher China tariffs, and reduction in job growth by 18 million jobs by 2045 compared with the baseline.
3. *Lower fuel and transportation costs.*[7] Scenario of low oil prices, reduced transportation cost, lower inflation, lower business costs, and additional job growth by 6.0 million jobs.

Each of these alternative futures leads to a different mix of growth among industry sectors, as well as among locations. These differences are illustrated in the maps shown in Figures D-21–D-23 and as graphs in Figures D-A1 and D-A2 in the Addendum.

1. *Stronger U.S. economic prosperity.* This scenario (see Figure D-21) shows greater output and job growth, compared with the baseline scenario. The shift is still greatest in specific "growth hotspots" in

[5] Moody's Analytics (2017) scenario "Stronger Near-Term Growth," with temporary effects to 2020 extrapolated to persist to 2030.

[6] Moody's Analytics (2017) scenario "Protracted Slump," with temporary effects to 2020 extrapolated to persist to 2030.

[7] Moody's Analytics (2017) scenario "Low Oil Price," with temporary effects to 2020 extrapolated to persist to 2030.

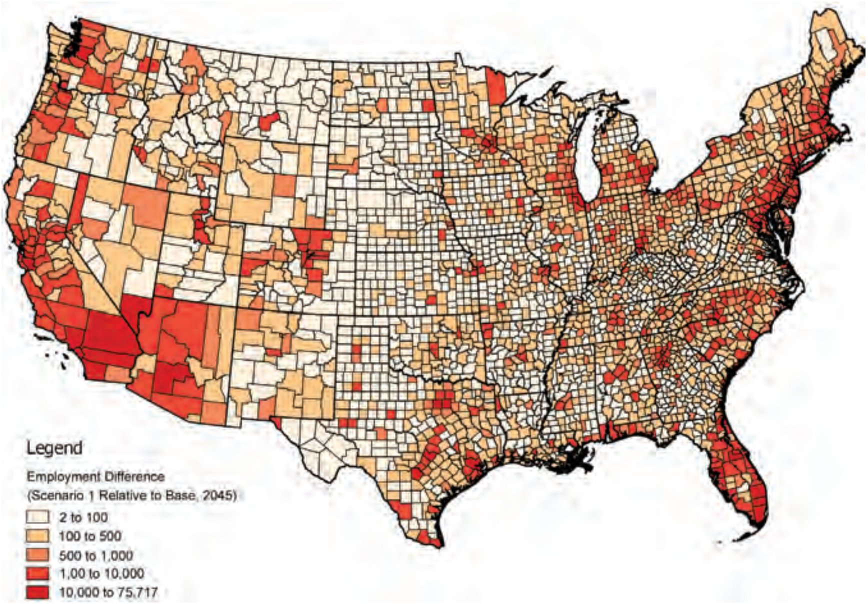

FIGURE D-21 Jobs in stronger U.S. economic prosperity scenario compared with baseline, 2045.

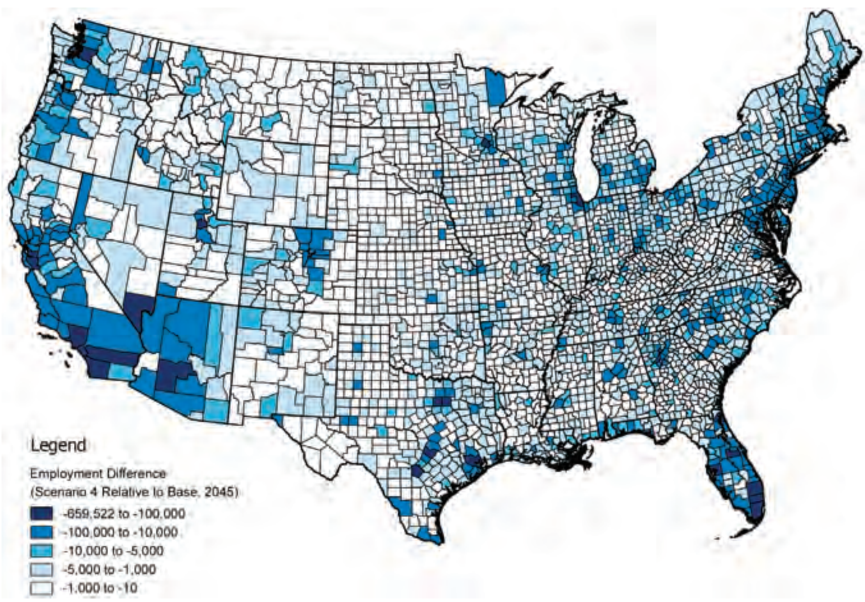

FIGURE D-22 Jobs in protracted economic slump scenario compared with baseline, 2045.

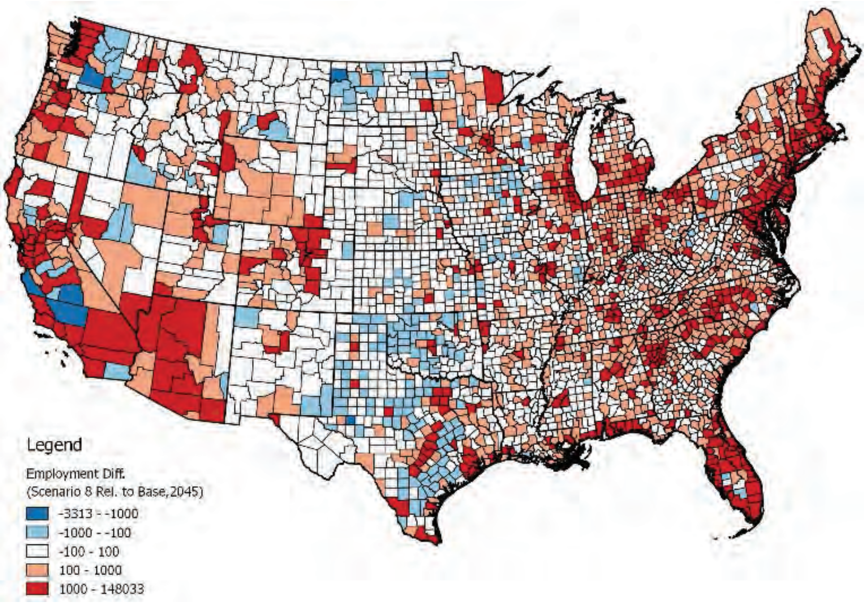

FIGURE D-23 Jobs in reduced fuel cost scenario compared with baseline, 2045.

metropolitan areas, particularly the megaregions. Growth of service industries is more dispersed. The overall effect of this scenario is to accentuate the magnitude of growth in areas that are already growth hotspots.

2. *Protracted economic slump*. This scenario (see Figure D-22) represents more than a temporary recession. Job growth is reduced considerably, which again mostly affects the growth hotspots in metropolitan areas and particularly the megaregions. Negative effects on service industries are more widely dispersed. The overall effect of this scenario is to diminish the magnitude of growth in areas that are already growth hotspots.
3. *Lower fuel und transportation costs*. The "reduced fuel cost" scenario (see Figure D-23) has a more spatially distinct impact. Lower fuel prices reduce cost (and increase productivity) for producers and consumers. However, they negatively affect profits for energy industries and their supply chains. Petroleum and shale production areas can see particularly negative impacts.

As each future change occurs in industry composition and location patterns, there will be corresponding shifts in origin–destination patterns for both commuting and freight movements. To portray these shifts in traffic movements, it is necessary to first consider matrices of interindustry (buy and sell) relationships and their spatial characteristics, and then consider how the forecast industry location shifts will affect them. The outcome of this process is illustrated in Figure D-24, which shows the expected impact on freight movements for the scenario of lower fuel costs. Similar types of calculations and visualizations can also be done for other scenarios. This scenario was chosen to illustrate the effect because it presents clear GDP impacts that differ substantially among industries and that lead to significant changes in freight movement patterns, volumes, and distances (affecting tonnage and ton miles), all of which can then be assigned to the highway network. The scenario in Figure D-24 shows reductions in freight tonnage (blue lines) on highway routes in those parts of the country that produce petroleum and shale oil (which suffer revenue losses from lower oil prices). The scenario shows an increase in freight tonnage (red lines) on highway routes where manufacturers and shippers gain productivity and profitability.

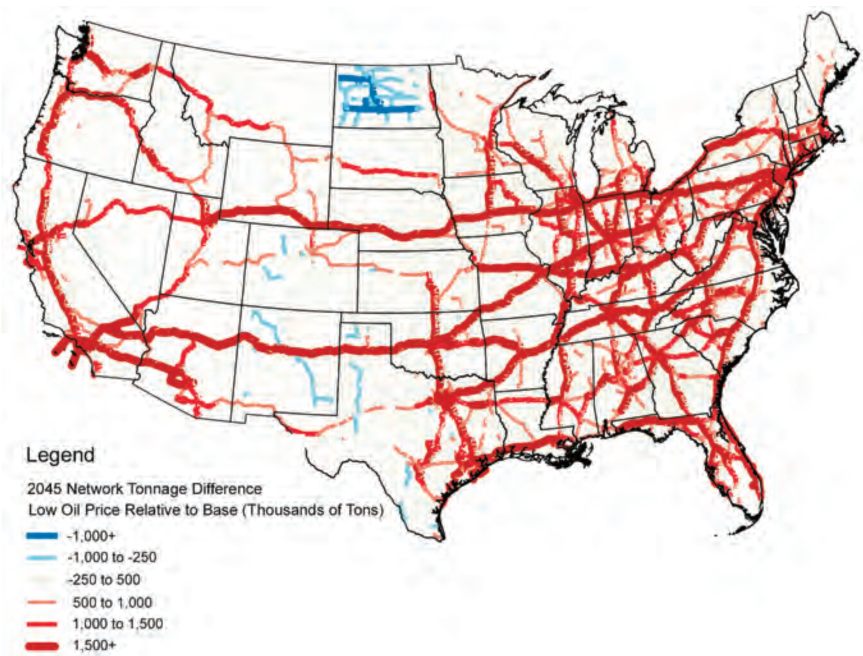

FIGURE D-24 Changes in freight flows for the lower fuel and transportation costs scenario.

Additional Sources of Future Economic Change: Planning Under Uncertainty Conditions

Difference Between Economic Factors and Other Uncertainty Factors

The preceding section discussed uncertainties about the economy, with alternative assumptions regarding *economic factors* such as evolving long-term shifts in trade, inflation, investment, and prices, which can affect the future pattern of industry and spatial economic growth. This section discusses *other uncertainties* that can also affect the economy (and hence highway VMT), although their cause may be geopolitical, site or geological, or climate related rather than aspects of the economy itself.

- *Geopolitical/trade factors* tend to focus on relationships between countries, usually via tariffs (although they may also include embargoes) that have the long-term effect of shifting import/export flows among certain combinations of nations. For instance, changes in trade with China, Mexico, South America, and Russia have all been discussed in the press as possibilities for the future. In many cases, extending these shifts among international trade partners means extending shifts among West Coast, East Coast, or Gulf Coast seaports, or sometimes also affecting Canadian and Mexican border movements. Changes in use of the Panama or Suez canals can have similar spatial economic effects.
- *Severe site events* can knock out specific airports, bridges, or highway links for an extended period. To varying degrees, such facilities are used for domestic or international business activities (freight imports and exports, worker travel, or customer or visitor travel). Consequently, events affecting use of those facilities can also have economic impacts on specific affected industries and areas and can also lead to shifts in highway demand for long periods of time. They include
  - *geological factors* such as severe earthquakes, volcanoes, tsunamis, and landslides;
  - *structural failures* such as collapse of a major bridge, tunnel, or viaduct structure;
  - *weather events* such as a tornado or hurricane; and
  - *terrorist actions* such as bombs that knock out ports or terminals or highways that serve them.

Although it is not possible to predict where these site events will occur, it is possible to rate sites by their vulnerability to such events and then apply

Monte Carlo simulations to calculate the economic impact of such events taking place at different locations. From an economic impact perspective, the cause does not necessarily matter. After all, multiple causes can lead to the same direct impact on a site and then produce similar impacts on certain industries and regions.

- *Climate factors* can have long-term consequences for the viability of economic activities that are located along ocean, lake, and river coasts, or that depend on access corridors through those areas. These effects tend to affect broad areas due to regional coast flooding (affected by rising sea levels), river valley flooding (affected by melting mountain ice), or forest/brush fires (affected by heat and drought). The severity of weather events is also exacerbated by climate change.

In all cases, regardless of the reason for uncertainty, economic impact will occur insofar as specific industry or location concentrations are particularly hard hit. The highway VMT consequences follow from the economic activity shifts.

Example: International Trade Shift

We can illustrate the distortion effect on highway freight VMT by considering the example of an international trade policy that shifts U.S. grain exports so that more go to Asia and less to Mexico. This example was developed by applying a trade impact scenario via TREDPLAN,[8] based on Moody's baseline forecast[9] and international trade patterns from WISERTrade.[10]

In this example, shown in Figure D-25, there is a *gain* of activity at various ports that directly serve Asia (mostly West Coast), or that serve Asia via the Panama Canal (Gulf Coast and Southeast United States). There is a corresponding *loss* of activity at various land ports (border crossings) at the Mexican border, as well as a smattering of smaller airports located farther away (used for shipping specialty products).

The affected highway corridors were identified based on origin–destination patterns of grain export shipments. They are shown in Figure D-26. Apparent impacts include less reliance on congested I-35 in Texas and higher dependence on access to Seattle and congested California ports.

[8] See https://www.tredis.com/products/tredplan.
[9] See https://www.economy.com/products/alternative-scenarios.
[10] See http://www.wisertrade.org/home/portal/index.jsp.

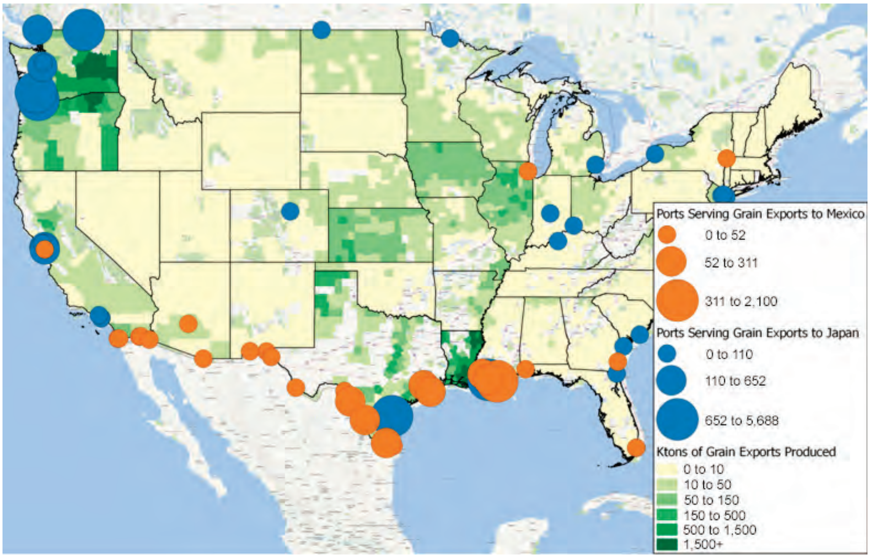

FIGURE D-25 Illustration of ports affected by shift of U.S. grain exports to Asia instead of Mexico.

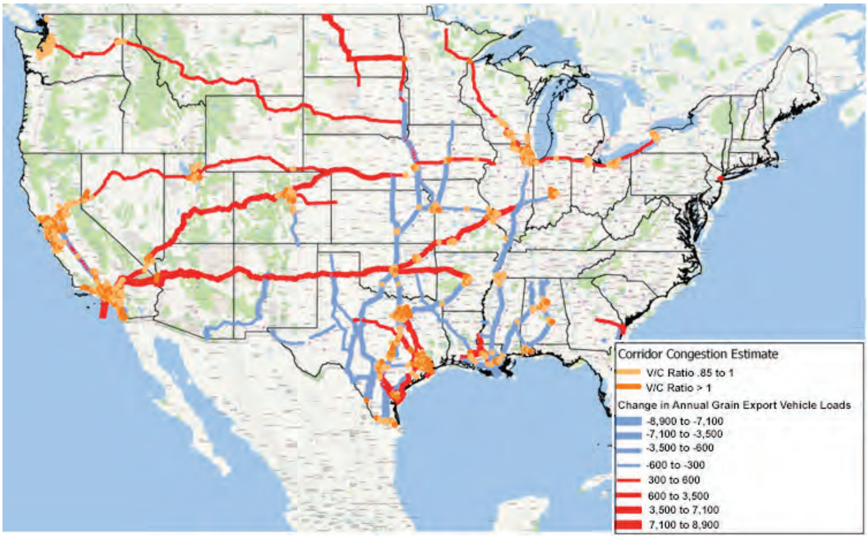

FIGURE D-26 Highway traffic links affected by shift of U.S. grain exports to Asia instead of Mexico.

CONCLUSIONS AND NEXT STEPS

This section summarizes findings to date and issues that remain to be addressed.

Findings to Date

This appendix has shown how evolving changes in the U.S. economy will lead to critical changes in the location of generated highway traffic, car and truck mix, and origin–destination patterns of highway traffic. This finding can have profound implications for the future adequacy of the Interstate Highway System network and for the location of congestion points, and it can affect investment priorities to support our nation's continued economic vitality.

More generally, the appendix provides a base of information about economic drivers that influence demand for Interstate highways and their metropolitan area extensions. It shows how the U.S. economy has evolved and will continue to evolve differently, with shifts occurring in patterns of jobs, income, and business output (GDP). It shows how these patterns are shifting among industries (sectors of the economy) and locations of economic activity—which also affects population movements and highway traffic patterns. It means that even if the Interstate System has adequate capacity for anticipated VMT growth, that capacity may not be located where it is most needed.

The analysis of alternative futures also showcases how economic uncertainty factors regarding global growth and transportation-related fuel prices can affect longer-term economic patterns across the United States. It shows that changes in current exchange rates, investments, and prices do not just affect overall growth rates across the board; they can also affect some industries and locations more than others. This finding can also have important consequences for assessing risk of either overinvestment in highway infrastructure with resulting stranded assets, or underinvesting in highway infrastructure with resulting capacity shortfalls and foregone economic productivity. In fact, both conditions can occur simultaneously, along different parts of the Interstate Highway System.

Next Steps: Remaining Research Needs

This appendix focused on establishing the economic determinants of VMT change. More work is needed to apply this information to develop models and forecasts of future VMT on the Interstate System. In particular, there is a need to develop forecasts of *multiple alternative futures* based on projections of the trip generation and origin–destination consequences of changes in international trade, domestic trade, and other economic change scenarios.

In addition to better developing VMT projections, more work is needed to develop alternative economic futures in sufficient detail to support a robust *risk and uncertainty analysis*. More work is also needed to apply these uncertainties to a complete highway network model to identify where the risks and vulnerabilities of the Interstate Highway System are greatest.

Finally, to move forward in planning for the future of the Interstate Highway System, there will be a need to consider the nation's *economic dependence* on the Interstate Highway System and the economic consequences of inadequately investing where capacity and performance are most critically needed. The work reported in this appendix provides a starting basis and structure for moving forward on this topic.

REFERENCES

Abbreviations

BTS	Bureau of Transportation Statistics
FHWA	Federal Highway Administration

BTS. 2017a. *Table 1-35: U.S. Vehicle-Miles (Millions)*. National Transportation Statistics. U.S. Department of Transportation, Washington, D.C. https://www.bts.gov/archive/publications/national_transportation_statistics/table_01_35.

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ADDENDUM

Freight Intensity Estimation

Freight intensity of demand is an ad hoc measure designed to reflect the spatial concentration of industries that demand a high level of freight goods for their production processes. This was estimated by using an input-output model (IMPLAN version 536, sector detail) and calculating the value of inputs related to bulk commodity goods[11] as a percentage of total economic output of that industry. The industries were aggregated to a 53-sector grouping and graphically sorted based on intensity to identify an approximate break in the intensity of demand. The red bars in Figure D-A1 indicate manufacturing industries with a higher than average freight demand. The blue bars indicate industries that have a lower than average freight demand. This calculated ratio is used in the section on key differences in highway reliance among industries (see Figures D-6 and D-7) and in the section on highway travel implications of baseline economic change (see Figure D-17) to show the spatial pattern of freight-intensive industries in the economy of each county. Of course, using these same ratios for comparisons over time assumes that production functions and capital/labor ratios do not change materially among industries over time. (That assumption can be refined in further studies.)

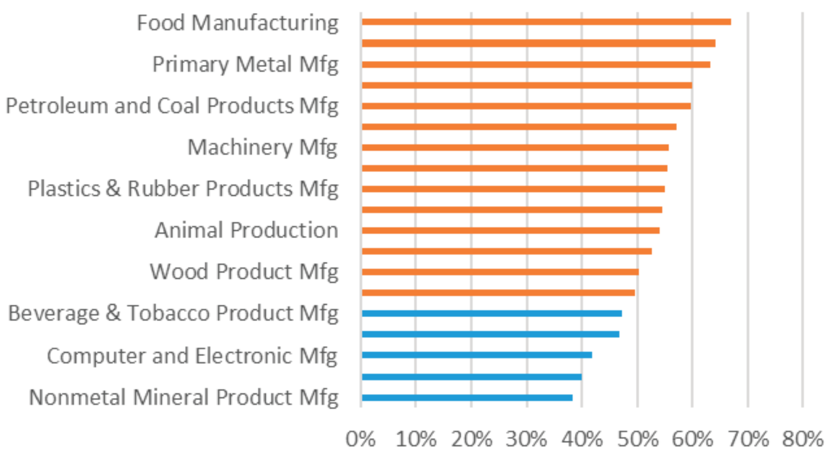


FIGURE D-A1 Identification of industries with highest intensity of freight demand (fraction of output, 53 sectors).

[11] Based on the Standard Classification of Transported Goods.

Baseline Scenario Over 50 Years

The following tables show baseline forecasts for 2015–2065 in terms of employment and output.

TABLE D-A1 Baseline Employment by Industry Over Time

	Employment (jobs)				
Industry	**2015**	**2025**	**2035**	**2045**	**2065**
Crop production	1,504,219	1,553,335	1,437,193	1,308,874	1,052,234
Animal production	1,167,083	1,213,600	1,128,760	1,030,862	835,066
Forestry and logging	144,994	153,717	142,696	130,451	105,961
Fishing, etc.	111,784	113,921	104,981	95,629	76,924
Support for agriculture and forestry	543,932	548,091	505,459	460,254	369,845
Oil and gas extraction	813,174	809,828	755,166	691,787	565,030
Mining, quarrying, and support	768,207	758,842	705,784	642,296	515,320
Utilities	684,932	673,233	647,567	601,346	508,904
Construction and buildings	10,156,166	12,472,113	13,189,748	14,122,909	15,989,230
Food manufacturing	1,806,898	1,773,716	1,553,541	1,294,188	775,481
Beverage and tobacco product manufacturing	247,889	242,653	212,101	176,432	105,092
Textile mills and products manufacturing	247,249	218,213	188,978	177,739	155,259
Apparel manufacturing	175,023	153,378	132,910	124,782	108,525
Leather product manufacturing	34,323	30,746	27,107	25,688	22,851
Wood product manufacturing	447,265	412,290	369,860	344,538	293,894
Paper manufacturing	376,600	346,021	309,344	287,660	244,294
Printing	557,848	500,048	440,331	417,149	370,784
Petroleum and coal products manufacturing	115,264	108,615	96,752	87,210	68,127
Chemical manufacturing	789,829	728,788	636,208	564,808	422,009
Plastics and rubber products manufacturing	707,430	648,666	560,229	491,749	354,789
Nonmetal mineral product manufacturing	428,006	387,527	343,319	324,396	286,551

continued

TABLE D-A1 Continued

	Employment (jobs)				
Industry	**2015**	**2025**	**2035**	**2045**	**2065**
Primary metal manufacturing	405,483	345,648	293,973	294,099	294,350
Fabricated metal manufacturing	1,515,650	1,292,039	1,099,951	1,082,180	1,046,636
Machinery manufacturing	1,145,136	969,793	825,621	775,851	676,310
Computer and electronics manufacturing	968,065	889,448	763,589	672,061	489,004
Electrical equipment and appliance manufacturing	401,509	368,426	327,094	301,570	250,520
Transportation equipment manufacturing	1,613,540	1,588,006	1,631,493	1,625,293	1,612,893
Furniture manufacturing	420,986	404,183	382,307	357,701	308,490
Miscellaneous manufacturing	680,610	624,546	556,892	516,722	436,382
Wholesale trade	6,443,610	5,912,392	5,274,378	4,891,133	4,124,645
Retail trade	18,026,221	19,241,384	19,533,894	20,742,242	23,158,938
Air transportation	492,667	511,947	508,301	493,861	464,982
Rail transportation	208,010	213,176	211,272	204,986	192,413
Water transportation	76,415	77,736	76,778	74,079	68,681
Truck transportation	2,114,043	2,187,086	2,173,695	2,113,140	1,992,030
Transit and ground transportation	1,081,420	1,123,903	1,132,230	1,122,827	1,104,022
Pipeline transportation	49,589	51,639	51,699	50,407	47,824
Scenic and sightseeing transport support	732,246	850,774	936,574	1,075,197	1,352,442
Couriers, messengers and postal service	1,516,438	1,648,381	1,745,696	1,843,748	2,039,853
Warehousing and storage	1,022,957	1,094,506	1,115,386	1,081,879	1,014,864
Media and information	3,356,782	3,408,581	3,403,326	3,452,451	3,550,702
Finance and insurance	9,939,217	10,805,384	11,819,397	13,378,990	16,498,175
Real estate, rental, and leasing	8,125,814	8,958,662	10,116,908	11,784,507	15,119,706

TABLE D-A1 Continued

	Employment (jobs)				
Industry	**2015**	**2025**	**2035**	**2045**	**2065**
Professional, scientific, and technical	14,400,183	16,149,377	17,534,598	19,135,320	22,336,762
Management services	2,354,727	2,680,167	2,987,841	3,343,850	4,055,869
Business services (administration, support, waste)	11,972,258	13,390,775	14,431,016	15,630,989	18,030,935
Education services	3,708,034	4,059,884	4,406,005	4,725,075	5,363,214
Health care and social assistance	21,185,100	23,665,834	25,586,549	27,797,594	32,219,684
Arts, entertainment, and recreation	4,064,867	4,691,052	5,142,333	5,879,001	7,352,337
Lodging	1,488,830	1,729,720	1,905,623	2,191,752	2,764,011
Restaurants and drinking establishments	13,047,911	15,107,136	16,598,909	19,013,447	23,842,524
Other services	11,856,998	13,188,597	14,107,001	15,175,911	17,313,730
Government (public administration)	22,565,361	24,065,241	25,622,095	27,072,716	29,973,957

TABLE D-A2 Baseline Output by Industry Over Time

	Output (millions of dollars)				
Industry	**2015**	**2025**	**2035**	**2045**	**2065**
Crop production	200,447	225,019	256,185	280,998	330,625
Animal production	203,998	241,716	277,261	307,020	366,537
Forestry and logging	11,837	14,698	16,661	18,288	21,542
Fishing, etc.	7,445	9,732	11,211	12,340	14,599
Support for agriculture and forestry	34,491	41,347	47,606	52,628	62,672
Oil and gas extraction	216,618	233,636	213,487	191,264	146,819
Mining, quarrying, and support	231,886	250,238	227,278	200,110	145,775
Utilities	756,043	880,407	959,780	1,015,325	1,126,416
Construction	1,703,879	2,105,786	2,209,755	2,261,891	2,366,164
Food manufacturing	955,854	902,133	878,139	863,954	835,584
Beverage and tobacco product manufacturing	218,969	210,549	209,184	209,878	211,264

continued

TABLE D-A2 Continued

	Output (millions of dollars)				
Industry	**2015**	**2025**	**2035**	**2045**	**2065**
Textile mills and products manufacturing	66,132	67,216	67,716	67,793	67,948
Apparel manufacturing	19,823	20,379	20,248	19,860	19,083
Leather product manufacturing	8,070	8,330	8,270	8,129	7,847
Wood product manufacturing	106,328	134,466	168,957	207,410	284,316
Paper manufacturing	225,308	274,032	332,838	396,485	523,778
Printing	90,469	93,109	91,817	89,772	85,683
Petroleum and coal products manufacturing	451,997	573,415	673,650	784,554	1,006,361
Chemical manufacturing	1,174,022	1,429,874	1,670,998	1,938,843	2,474,533
Plastics and rubber products manufacturing	246,803	292,234	333,835	379,070	469,539
Nonmetal mineral product manufacturing	135,735	167,923	206,456	247,168	328,592
Primary metal manufacturing	281,137	330,562	384,827	432,084	526,598
Fabricated metal manufacturing	395,002	469,410	556,883	635,857	793,804
Machinery manufacturing	496,023	563,837	662,953	765,445	970,429
Computer and electronics manufacturing	550,279	859,682	1,331,497	1,932,443	3,134,333
Electrical equipment and appliance manufacturing	162,465	203,281	256,307	317,309	439,313
Transportation equipment manufacturing	1,124,302	1,496,830	1,905,149	2,232,592	2,887,479
Furniture manufacturing	82,382	94,008	106,308	117,504	139,895
Miscellaneous manufacturing	189,949	239,284	297,830	362,965	493,235
Wholesale trade	1,655,910	2,073,713	2,580,157	3,145,545	4,276,322
Retail trade	1,472,336	1,889,020	2,376,010	2,915,317	3,993,930
Air transportation	202,027	268,796	342,445	430,541	606,734
Rail transportation	84,438	108,380	136,113	169,230	235,463
Water transportation	62,514	83,829	106,066	130,161	178,350
Truck transportation	349,964	454,628	570,930	710,173	988,659
Transit and ground transportation	73,832	91,492	109,817	130,587	172,127

TABLE D-A2 Continued

	Output (millions of dollars)				
Industry	**2015**	**2025**	**2035**	**2045**	**2065**
Pipeline transportation	35,734	47,218	61,352	78,240	112,017
Scenic and sightseeing transport support	123,116	162,613	205,658	256,390	357,854
Couriers, messengers, and postal service	162,065	200,763	243,780	293,329	392,429
Warehousing and storage	104,703	151,911	217,731	308,081	488,781
Media and information	1,639,214	2,217,025	2,815,322	3,531,935	4,965,162
Finance and insurance	2,441,631	2,843,859	3,153,913	3,469,123	4,099,543
Real estate, rental, and leasing	3,231,264	3,764,937	4,166,190	4,577,163	5,399,109
Professional, scientific, and technical	2,368,846	3,144,850	3,993,965	4,974,890	6,936,739
Management services	573,327	756,200	953,161	1,179,644	1,632,611
Business services (administration, support, waste)	854,640	1,140,949	1,456,972	1,824,483	2,559,504
Education services	270,411	335,960	420,752	511,106	691,814
Health care and social assistance	2,104,237	2,641,309	3,340,731	4,102,232	5,625,235
Arts, entertainment, and recreation	323,475	407,984	502,922	608,348	819,200
Lodging	160,853	204,828	254,758	310,118	420,839
Restaurants and drinking establishments	785,304	988,863	1,222,948	1,487,741	2,017,327
Other services	985,886	1,312,254	1,668,414	2,079,417	2,901,423
Government (public administration)	2,306,486	2,659,056	3,096,137	3,550,682	4,459,772

Changes in Characteristics of the Economy

The following tables show forecasts of change in the industry mix, productivity, and trip distances over 2015–2045.

TABLE D-A3 Economic Shifts by Industry, 2015–2045

	Distribution of Employment (%)		Distribution of GDP (%)	
Industry	**2015**	**2045**	**2015**	**2045**
Crop production	0.80	0.57	0.50	0.41
Animal production	0.62	0.45	0.37	0.31
Forestry and logging	0.08	0.06	0.04	0.03
Fishing, etc.	0.06	0.04	0.03	0.03
Support for agriculture and forestry	0.29	0.20	0.15	0.13
Oil and gas extraction	0.43	0.30	0.86	0.44
Mining, quarrying, and support	0.41	0.28	0.79	0.40
Utilities	0.36	0.26	1.72	1.33
Construction	5.38	6.11	4.29	3.23
Food manufacturing	0.96	0.56	1.00	0.51
Beverage and tobacco product manufacturing	0.13	0.08	0.44	0.24
Textile mills and products manufacturing	0.13	0.08	0.10	0.06
Apparel manufacturing	0.09	0.05	0.04	0.02
Leather product manufacturing	0.02	0.01	0.01	0.01
Wood product manufacturing	0.24	0.15	0.17	0.19
Paper manufacturing	0.20	0.12	0.31	0.31
Printing	0.30	0.18	0.23	0.13
Petroleum and coal products manufacturing	0.06	0.04	0.88	0.85
Chemical manufacturing	0.42	0.24	1.83	1.71
Plastics and rubber products manufacturing	0.37	0.21	0.42	0.37
Nonmetal mineral product manufacturing	0.23	0.14	0.27	0.28
Primary metal manufacturing	0.21	0.13	0.32	0.28
Fabricated metal manufacturing	0.80	0.47	0.82	0.75
Machinery manufacturing	0.61	0.34	0.83	0.72
Computer and electronic manufacturing	0.51	0.29	1.40	2.86

TABLE D-A3 Continued

	Distribution of Employment (%)		Distribution of GDP (%)	
Industry	**2015**	**2045**	**2015**	**2045**
Electrical equipment and appliance manufacturing	0.21	0.13	0.30	0.33
Transportation equipment manufacturing	0.85	0.70	1.56	1.76
Furniture manufacturing	0.22	0.15	0.15	0.12
Miscellaneous manufacturing	0.36	0.22	0.45	0.49
Wholesale trade	3.41	2.11	5.91	6.40
Retail trade	9.55	8.97	5.41	6.12
Air transportation	0.26	0.21	0.49	0.60
Rail transportation	0.11	0.09	0.25	0.29
Water transportation	0.04	0.03	0.10	0.12
Truck transportation	1.12	0.91	0.80	0.92
Transit and ground transportation	0.57	0.49	0.19	0.20
Pipeline transportation	0.03	0.02	0.14	0.18
Scenic and sightseeing transport support	0.39	0.46	0.36	0.42
Couriers, messengers, and postal service	0.80	0.80	0.60	0.62
Warehousing and storage	0.54	0.47	0.34	0.57
Media and information	1.78	1.49	4.73	5.77
Finance and insurance	5.26	5.78	7.20	5.75
Real estate, rental, and leasing	4.30	5.09	12.53	10.12
Professional, scientific, and technical	7.63	8.27	8.21	9.82
Management services	1.25	1.45	2.01	2.35
Business services (administration, support, waste)	6.34	6.76	3.19	3.88
Education services	1.96	2.04	0.97	1.05
Health care and social assistance	11.22	12.02	7.35	8.17
Arts, entertainment, and recreation	2.15	2.54	1.04	1.11
Lodging	0.79	0.95	0.58	0.64
Restaurants and drinking establishments	6.91	8.22	2.50	2.70

continued

TABLE D-A3 Continued

	Distribution of Employment (%)		Distribution of GDP (%)	
Industry	**2015**	**2045**	**2015**	**2045**
Other services	6.28	6.56	2.77	3.34
Government (public administration)	11.95	11.70	12.04	10.57
Total	100.00	100.00	100.00	100.00

TABLE D-A4 Shifts in Freight Shipping Distances, 2015–2045

Tonnage Driven Statistics	2015	Change, 2015–2045 (%)
Ton miles	6,993,628.98	40
0–50 miles	50,871	64
51–100 miles	150,784	62
101–200 miles	345,974	56
201–500 miles	859,608	57
501+ miles	5,586,392	36
Vehicle-miles traveled	1,274,134	41
0–50 miles	9,587	64
51–100 miles	28,596	62
101–200 miles	63,238	56
201–500 miles	191,986	57
501+ miles	980,727	36

TABLE D-A5 Changes in Productivity and Income by Industry, 2015–2045

Industry	Change in Output per Employee, 2015–2045 (%)	Change in Income per Employee, 2015–2045 (%)
Crop production	61	66
Animal production	70	66
Forestry and logging	72	74
Fishing, etc.	94	93
Support for agriculture and forestry	80	77
Oil and gas extraction	4	5
Mining, quarrying, and support	3	7
Utilities	53	53
Construction	-5	-5
Food manufacturing	26	26

TABLE D-A5 Continued

Industry	Change in Output per Employee, 2015–2045 (%)	Change in Income per Employee, 2015–2045 (%)
Beverage and tobacco product manufacturing	35	30
Textile mills and products manufacturing	43	41
Apparel manufacturing	41	38
Leather product manufacturing	35	33
Wood product manufacturing	153	154
Paper manufacturing	130	130
Printing	33	32
Petroleum and coal products manufacturing	129	127
Chemical manufacturing	131	122
Plastics and rubber products manufacturing	121	119
Nonmetal mineral product manufacturing	140	139
Primary metal manufacturing	112	110
Fabricated metal manufacturing	125	124
Machinery manufacturing	128	126
Computer and electronics manufacturing	406	398
Electrical equipment and appliance manufacturing	160	162
Transportation equipment manufacturing	97	94
Furniture manufacturing	68	67
Miscellaneous manufacturing	152	150
Wholesale trade	150	150
Retail trade	72	72
Air transportation	113	113
Rail transportation	103	102
Water transportation	115	114
Truck transportation	103	103
Transit and ground transportation	70	63
Pipeline transportation	115	127

continued

TABLE D-A5 Continued

Industry	Change in Output per Employee, 2015–2045 (%)	Change in Income per Employee, 2015–2045 (%)
Scenic and sightseeing transport support	42	41
Couriers, messengers, and postal service	49	47
Warehousing and storage	178	178
Media and information	109	108
Finance and insurance	6	5
Real estate, rental, and leasing	-2	0
Professional, scientific, and technical	58	58
Management services	45	44
Business services (administration, support, waste)	64	63
Education services	48	48
Health care and social assistance	49	48
Arts, entertainment, and recreation	30	30
Lodging	31	31
Restaurants and drinking establishments	30	30
Other services	65	65
Government (public administration)	28	29

Alternative Scenarios

The alternative scenarios used here have a common property: strong and differing assumptions about economic conditions over the first 10 years (2015–2025), followed by an adjustment toward equilibrium (diminishing the severity of the trend) over the next 5 years (2015–2025), with earlier gains or losses then sustained for the rest of the study period (2025–2045). Impacts beyond that time frame are merely extrapolations of the 2035–2045 trends.

These scenarios were derived from Moody's Analytics scenarios, but adjusted to reflect more sustained long-term economic impacts. Whereas the original Moody's scenarios assumed a 10-year period of economic shock and equilibrium adjustment, the forecasts shown here sustain the impacts over a longer 20-year period. In any case, it is notable that the employment difference among scenarios in (see Figure D-A2) is substantially greater than the output difference among scenarios (see Figure D-A3).

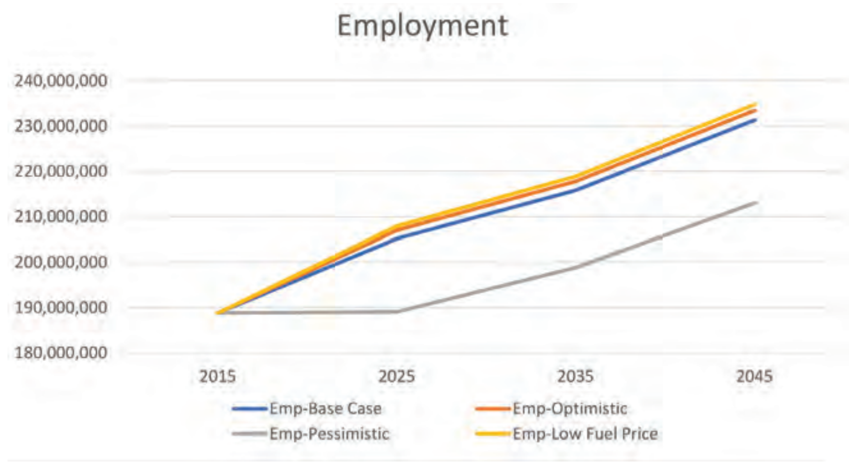


FIGURE D-A2 Projections of employment by scenario.

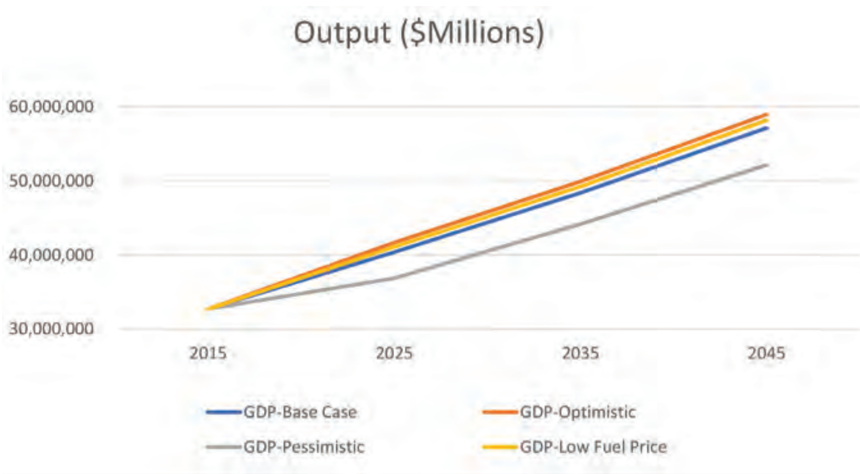


FIGURE D-A3 Projections of output by scenario.

Note that output (rather than GDP) has some advantage for forecasting changes in travel demand because it reflects the total value of goods produced and goods shipped (whereas GDP reflects the portion of output value that is incremental personal and business income). GDP is roughly 55 percent of total output. (In 2015, GDP was $18 trillion whereas output was $33 trillion.)

Appendix E

Demographic Forecasting and Future Interstate Highway System Demands

Guangqing Chi

Highways have, since their creation, played an important role in transforming society and affecting population change (Baum-Snow 2007; Vandenbroucke 2008). The Interstate Highway Act was passed in 1956, and thus began the development of Interstate highway infrastructure in the United States. Now, the Interstate Highway System handles nearly 25 percent of the total vehicle-miles traveled and 40 percent of total truck traffic, with only 1.2 percent roadway centerline miles of the U.S. public road system.

Although the Interstate Highway System used to be a symbol of American growth and its economic machine, the Interstate Highway System (see Figure E-1) has rarely been expanded since its inception. The Interstate System's activities of today mainly upgrade existing highways rather than construct new ones. In 2002, the Executive Director of the National Academies' Transportation Research Board stated that a majority of the existing highway systems, especially the interstates and principal highways, would need to be revamped in the near future (Skinner 2002). In 2009 the Obama administration planned to heavily invest in the transportation infrastructure with the American Recovery and Reinvestment Act. Furthermore, in 2017 the Trump administration proposed to revitalize the transportation infrastructure.

In response to section 6021 of the Fixing America's Surface Transportation Act of 2015, this special report addresses the actions needed to upgrade and restore the Interstate Highway System as a premier system for meeting the growing and shifting demands of the 21st century. As part of

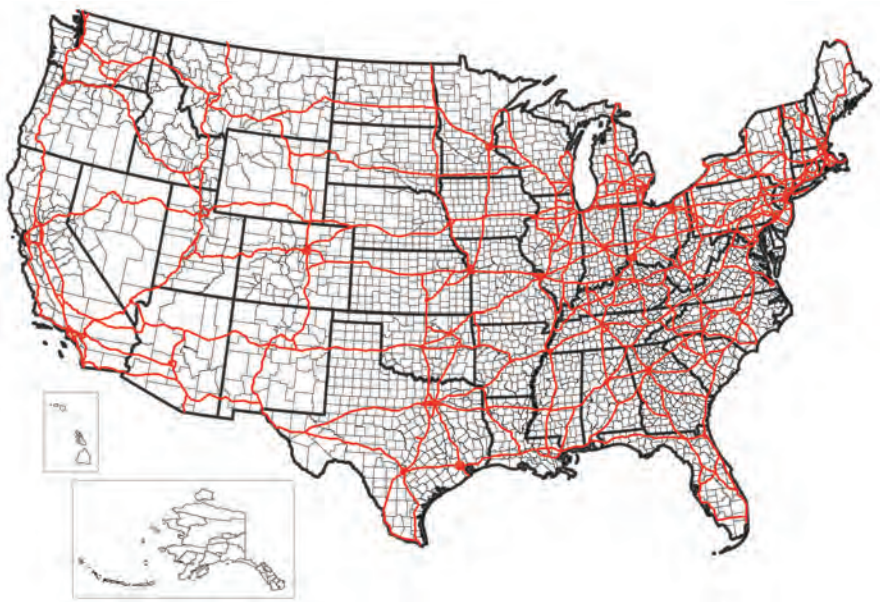


FIGURE E-1 Interstate Highway System in the United States.

this special report, this appendix focuses on demographic forecasting and future Interstate System demands. In particular, this appendix (1) provides up-to-date demographic information; (2) produces population projections into 2060 at the county level; (3) develops a method to identify counties that are projected to need additional (or less) Interstate capacity; and (4) discusses the implications of the aging population and baby boomers, the young population and millennials, immigrants, and telecommuting that affect travel demands.

POPULATION AND INTERSTATE HIGHWAY SYSTEM AS OF 2016

Overview of Literature on Population–Highway Dynamics

The relationship between population growth and highway investment has been studied in a vast literature that spans multiple disciplines, from sociology and geography to planning and economics. This diverse study base has resulted in a complex amalgam of empirical and theoretical approaches. While it is reasonable to assume that population–highway dynamics are two-directional, there is disproportionally more research on highway effects on growth than the other way around. The relationship between population change (or economic growth) and highway improvement[1] (or travel demand) has been found to be bidirectional and has feedback effects (Hobbs and Campbell 1967). Better highways or higher travel demand stimulate economic growth while the economic growth simultaneously increases demand for higher-quality highway access (Aschauer 1990; Mikelbank 1996). Highways cause population change and economic growth because the investment in highways alters the status quo of the social and economic balance. This, then, affects population growth or decline, depending on the locational advantage or disadvantage. Conversely, population change and economic growth affect travel demand and highways in that they have an influence on decisions about highway expansions—growth in the population and economy causes demand for reliable and high-quality transportation networks. Stephanedes and Eagle (1986) studied the interaction between highways and employment for 30 nonmetropolitan counties in Minnesota over a 25-year period. They found that investment in highways affected employment and then employment further affected investment in highways. In the following subsections, the literature on producing population projections for Interstate System planning is briefly summarized.

Highway Impacts on Population Change

Literature specifically examining the impacts of highways on population change is limited and mostly from the field of sociology (e.g., Chi 2010; Lichter and Fuguitt 1980; Perz et al. 2010; Voss and Chi 2006). There is, however, vast research on highway impacts on economic growth and development, as well as employment change, and it is supported by numerous theories and studies. The three most relevant theories are growth pole theory (Perroux 1955), neoclassical growth theory (Solow 1956), and central place theory (Christaller 1966).

Growth pole theory predicts mutual geographic dependence of development and economic growth between metropolitan areas and the surrounding rural areas using the concepts of spread and backwash; this dependence affects population change. In this theory, highways are considered a catalyst of change (Thiel 1962). Linking metropolitan areas to their surrounding areas by building a highway may not generate population growth in either area; population decline may also result.

Neoclassical growth theory states that generally there are three inputs that produce outputs: land, capital, and labor. Highway investments, as a type of public capital, may be considered an input through a production function, which assumes relationships between various inputs and

[1] Highway improvement, highway investment, and highway construction are used interchangeably in this appendix.

outputs (Eberts 1990). Many neoclassical growth theory studies examine the connection between public capital and economic productivity through the production function (e.g., Dalenberg and Partridge 1997). As applied to highways, this theory predicts that as highway infrastructures increase, economic output also increases, and this in turn produces both population and employment growth.

Central place theory considers the highway infrastructure to be a facilitator of consumers, raw materials, finished goods, capital, and idea flows between central locations and their surrounding neighborhoods (Thompson and Bawden 1992). Therefore, highway infrastructure can be considered a facilitator of population flows as well, because it may promote both population inflows and outflows, depending on overall population redistribution trends and other factors affecting population change. Highways in and of themselves, however, do not cause changes in population.

However, dissimilar, even contradictory, findings have been reported by empirical studies of varying geographic scales on the impacts of highways on population and economic change. For example, highways were found to have no or only minor effects on population and economic growth in some studies (e.g., Hulten and Schwab 1984; Jiwattanakulpaisarn et al. 2009; Voss and Chi 2006) yet were found to promote both population growth and economic growth in other studies (e.g., Boarnet et al. 2005; Cervero 2003; Goetz et al. 2010).

These contradictory findings may result from the spatial heterogeneity of highway impacts. That is, the impacts of highways on population change differ across rural, suburban, and urban areas because these area types have different socioeconomic and demographic characteristics as well as residents who may perceive highways differently (Chi 2010). A study on the impacts of highway expansions on population change conducted in Wisconsin at the minor civil division level by Chi (2010) found differing impacts across rural, suburban, and urban areas: highway expansions were found to have indirect effects on population change in rural areas, direct and indirect effects in suburban areas, and no statistically significant effects in urban areas.

Population Impacts on Highway Investment

Although much literature examines and several theories explain the impact that highways have on population change and economic growth, very few studies examine the impact of population growth on decisions to build new or expand existing highways, despite the fact that criteria for highway expansion decisions exist at the federal and state planning levels (U.S. DOT et al. 1998; Wisconsin DOT 1983, 2003). These criteria include public concerns, safety and congestion, economic benefit and cost, roadway deficiencies, forecasts of future demand, and environmental impacts. A key indicator of safety and congestion is traffic volume. Traffic volume can increase slowly through natural regional growth, or it can increase abruptly from large in-migration. Public concern is a criterion because citizens are generally involved in the planning and decision process of constructing or expanding a highway through formal petitions and public hearings (Wisconsin DOT 2003).

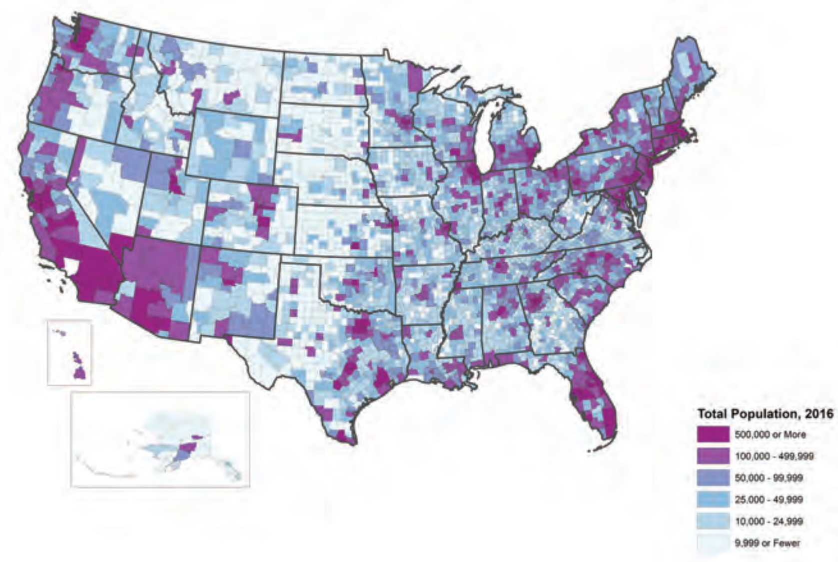
A study by Miller (1979) on nonmetropolitan U.S. counties in the late 1960s and early 1970s found that as highway construction began, population growth occurred, but then as construction was completed in the 1970s, population growth diminished. Lichter and Fuguitt (1980) also studied nonmetropolitan counties, comparing dates of highway completion to mean populations at the time. They found that the earlier the date of completion was, the larger the population size was. Their data also revealed that interstate highways were constructed in counties with previous high net in-migration. More recently, Voss and Chi (2006) found that the dominant causal influence between population growth and highway construction appears to flow from highway construction to population growth. Note that population and economic growth leads to higher travel demand, but does not necessarily lead to highway investments. The United States has seen little highway investments over the past three decades, although it experienced continual population and economic growth (Giuliano and Dargay 2006).

Overall, population growth and highway construction are closely related. In the transportation planning process, often a region is predicted to experience significant population growth so that highway construction or investment will follow. The rest of this appendix focuses on the causal direction from population growth to highway investment to predict population and identify areas that could need more (or less) Interstate capacity.

Population and Interstate Highway System in 2016

Figure E-2 shows total population and population density as of 2016 at the county level using the American Community Survey estimates of the Census Bureau. Populations are concentrated in the northwest corner of Washington and Oregon; California; lower Florida; the belt from Boston to Washington, D.C.; the belt from Minneapolis, Minnesota, to Pittsburgh, Pennsylvania, along I-90 and I-94; and from Atlanta, Georgia, to the Triangle of North Carolina.

The Interstate Highway System is correlated with population distribution (see Figure E-3). The nodes of the Interstate System are often located in high-density counties. This echoes the initial purpose of the Interstate



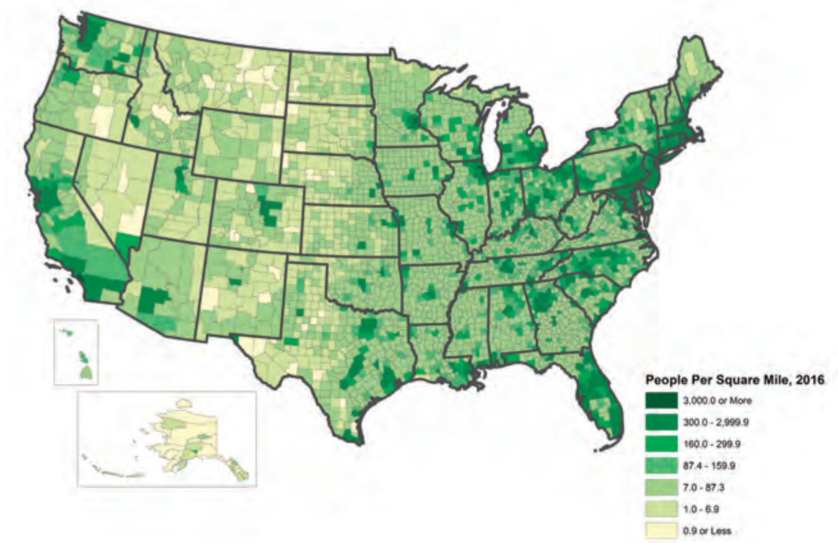


FIGURE E-2 Total population and population density as of 2016 in the United States.

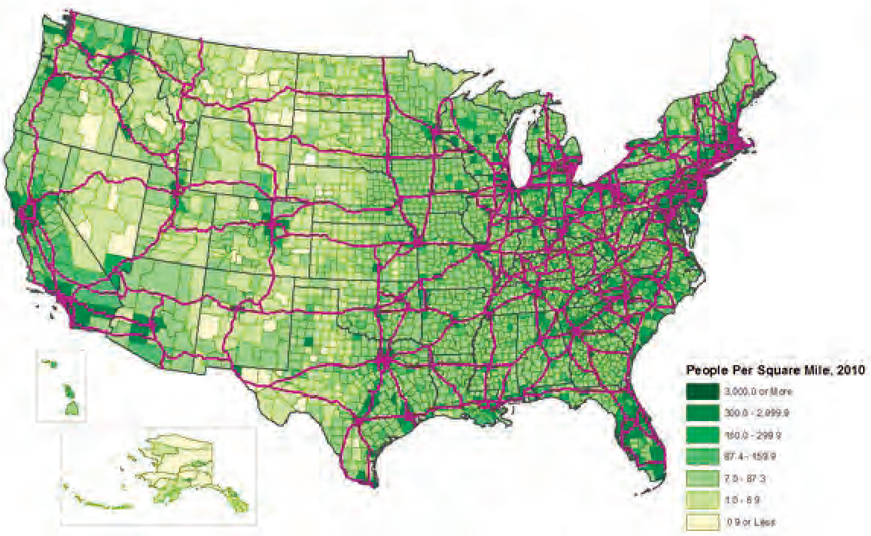


FIGURE E-3 Population Density in 2010 and the Interstate Highway System network.

Highway System, which is to connect principal cities and metropolitan areas and to serve the national defense (FHWA 1970).

How does population distribution relate to the Interstate System? In 2010, the 1,444 counties with Interstate highways had 178,412 people on average (see Table E-1). In contrast, the 1,698 counties without Interstates had 29,941 people on average. The Interstate Highway System serves a larger population beyond those in the counties where the system falls. Voss and Chi (2006) found that Interstate highways have an influence over 20 miles of flight distance. In total there are 2,477 counties that fall within 20 miles of the Interstate Highway System. These counties had an average of 119,080 people in 2010, compared to an average of 20,312 people in the 665 counties that fall beyond 20 miles of the Interstate System.

TABLE E-1 Descriptive Statistics of Population and Proximity to Interstate Highway System in 2010

	N	Mean	SD	Min.	Max.
Counties with Interstates	1,444	178,412	440,712	415	9,825,473
Counties without Interstates	1,698	29,941	78,950	83	2,510,240
Counties within 20 miles of the Interstate System	2,477	119,080	349,453	83	9,825,473
Counties beyond 20 miles of the Interstate System	665	20,312	29,348	90	293,415

POPULATION PROJECTIONS INTO 2060 AT THE COUNTY LEVEL

Projection Methodology, Procedure, and Assumptions

Cohort Component Methods

There are many methods for population forecasting, including extrapolation projections and time series models, postcensal population estimation models, knowledge-based regression models and structural models, conditional probabilistic models, integrated land use models, population forecasting by grid cells, and cohort component methods (Chi 2009; Smith et al. 2013; Wilson and Rees 2005). In this study, cohort component methods are selected to produce population projections into the future.

A study evaluating the projection accuracy of U.S. population projections from 1953 to 1999 (Mulder 2002) found that for a 10-year projection the mean percentage errors range from –18 percent to 30 percent and the mean absolute percentage errors range from 6 percent to 30 percent; and from –14 percent to 45 percent and from 12 percent to 45 percent respectively for a 20-year projection. Despite the large projection errors, cohort component methods provide the best projection accuracy (Smith et al. 2013). Cohort component methods are the default methods for population projections at the country, state, and county levels by the Census Bureau, state agencies that are in charge of their population projections, and commercial companies.

Cohort component methods project the three components of population change—births, deaths, and net migrants—separately for each birth cohort (i.e., persons born in a given year). The base population (by age, gender, and race or ethnicity) as of the projection launch year is projected each year by the projected survival rates and net migration rate. The births are projected and added to the population by applying the projected fertility rates to the female population. Cohort component methods produce population projection by age and gender for each year, and the projections are typically more accurate than what are produced by other methods at the county level and above (Smith et al. 2013). Population projections used in this paper are produced by the Census Bureau and ProximityOne (a population projection consulting firm) using cohort component methods. The methods and procedures are detailed in the next section. The projection produced by the Census Bureau is at the national level, while the projection produced by ProximityOne is at the county level. Projection accuracy is higher at the national level than that at the state level, and the latter is higher than that at the county level. This is because at finer levels the migration, which is the most difficult to predict among the three components of population change, can affect population change greatly, but the variation of net migration across space could cancel out each other at coarser (or aggregated) levels.

Population Estimates, Projections, and Forecasting

Population estimates, population projections, and population forecasting are often used in demographic forecasting work, but they refer to different things. Population estimates are estimates of a population on or before the current date. Population projections are predictions of a population into the future. For example, now it is April 2017. The Census Bureau has already released its population estimates for years 2011, 2012, 2013, 2014, 2015, and 2016. Projections are for 2017 and after. Both population estimates and projections are produced using methods based on some assumptions. Population estimates and projections are not observed facts—they reflect best efforts to accurately determine these values at specific points in time.

The difference between projections and forecasting is less obvious. A projection embodies one or more assumptions, and a forecast is a projection that is most likely to occur based on judgment. Nevertheless, "projection" and "forecast" are often used interchangeably.

Estimation or Projection Methodology

The population in year t as of July 1 for a county is estimated or projected as

$$P_t = P_{t-1} + B_{t-1,t} - D_{t-1,t} + M_{t-1,t}$$

where

t = year t, on July 1;
P_t = resident population as of July 1, year t;
P_{t-1} = resident population as of July 1, year $t - 1$;
$B_{t-1,t}$ = births during period (June 30)/$t - 1$ to (July 1)/t;
$D_{t-1,t}$ = deaths during period (June 30)/$t - 1$ to (July 1)/t; and
$M_{t-1,t}$ = net migrants during period (June 30)/$t - 1$ to (July 1)/t.

The baseline launch year is 2010 because it is the latest decennial year in which the Census Bureau conducted population counting and it provides the most complete population data. For each subsequent year, the people are aged/advanced 1 year of age. The population estimates or projections are a product of population in the previous year, plus births that occur during the 1-year period, minus deaths that occur during the 1-year period, and plus net migration that occurs during the 1-year period. That is,

$$P_{2011} = P_{2010} + B_{2010,2011} - D_{2010,2011} + M_{2010,2011}$$
$$P_{2017} = P_{2016} + B_{2016,2017} - D_{2016,2017} + M_{2016,2017}$$
$$P_{2060} = P_{2059} + B_{2059,2060} - D_{2059,2060} + M_{2059,2060}$$

Population estimates and projections are developed for each individual county. This is done for each age (0–84 and 85+ years) by gender and race/ethnicity. The race/ethnicity is categorized as non-Hispanic white, non-Hispanic black, Hispanics, and others. Note that age-, gender-, and race/ethnicity-specific rates are used for births, deaths, and migration. The rates are discussed in the sections following. Totally, the projection work produces

> 3,221 (counties) × 86 (age groups) × 2 (genders) × 4 (races/ethnicities) × 44 (projection years 2017–2060) = 97,506,112 projections for different combinations.

These elemental projections are then aggregated to each county for each year to produce total population projections for each county in each year.

Establishing Baseline (Launch Point) Population Data

The launch year is 2010 because that is the latest decennial year when the Census Bureau conducted population counting and it provides the most complete population data. The decennial census is based on April 1, 2010. However, it makes more sense to use the midyear as the point of reporting population. Plus, American Community Survey estimates are based on July 1. Therefore, before we begin, we need to adjust the decennial Census data from April 1, 2010, to July 1, 2010.

The baseline population data estimated as of July 1, 2010, will be partitioned by 86 age groups by 2 genders by 4 race/ethnicity groups for each county.

The baseline population data also single out populations in group quarters, which include college residence halls, nursing facilities, group homes, military quarters, correctional facilities, worker dormitories, and others. The populations in group quarters do not change from year to year in the same way that populations not in group quarters do because the former's age cohorts do not "age" each year. Therefore, the populations in group quarters are treated separately but are added to the final population projection.

Projecting Births

A new birth cohort is formed each year to be added to the population. For example, the cohort that is born between July 1, 2016, and June 30, 2017, is added to the population in 2017. Births are projected in three steps: (1) projecting age- and race/ethnicity-specific fertility rates; (2) applying the rates to the corresponding racial/ethnic female population age 15 to 54 years; and (3) splitting the births into boys and girls based on a boy–girl ratio. Overall, the age- and race/ethnicity-specific fertility rates decline over time. To avoid extreme change in the fertility rates, the decline in the crude birth rate for any county from 2010 to 2060 is limited to –0.05. If a county's crude birth rate is projected to decline more than 0.05 from 2010 to 2060, the decline is adjusted to 0.05.

Projecting Deaths

Deaths are subtracted from the population each year. For example, deaths that occurred between July 1, 2016, and June 30, 2017, are subtracted from the population in 2017. Deaths are projected in two steps: (1) projecting age-, gender-, and race/ethnicity-specific death rates for each county and (2) applying the rates to people of the corresponding age, gender, and race/ethnicity. Overall, the age-, gender-, and race/ethnicity-specific death rates increase over time. To avoid extreme change in the death rates, the increase in the crude death rate for any county from 2010 to 2060 is limited to 0.05. If a county's crude death rate is projected to increase more than 0.05 from 2010 to 2060, the increase is adjusted to 0.05.

Projecting Net Migration

Net migration is added to the population each year. For example, net migration between July 1, 2016, and June 30, 2017, is added to the population in 2017. Net migration is projected in two steps: (1) projecting age-, gender-, and race/ethnicity-specific net migration rates for each county and (2) applying the rates to people of the corresponding age, gender, and race/ethnicity. The migration rates are projected by following the migration patterns exhibited from 2010 to 2016.

Producing Total Population Projections

The total populations are projected for each county in each year by adding projected population from the previous year, births from the previous year, and net migration from the previous year and then subtracting deaths from the previous year.

In practice, population projections are often adjusted to improve forecasting accuracy. Adjusting population projections can involve many steps. Two major considerations are (1) modifications to rein in severely abnormal change rates and (2) adjustment to (or control of) national projections (Voss and Kale 1986). Modification of abnormal change (growth or decline) rates is used to soften the occasional high population change rates that emerge when making population projections. If the population change rate in a county is unusually high, the projected rate is softened under the assumption that rapid population change cannot be sustained for long periods. If a county is projected to have a population of fewer than 100 people or even negative population in any given year, the projected population is set at 100 people.

The projected populations for each county after adjustment are aggregated to the national level and compared and adjusted to the national population projections prepared by the Census Bureau. The latter is seen as the gold standard for population projections in the United States. However, the Census Bureau does not produce population projections for states or counties.

Note that the projections are made under the assumption that no major local or national disasters will occur between now and 2060. Unfortunately, this assumption becomes less valid as time passes. This is probably partly why the Census Bureau does not produce population projections for any subnational levels. This appendix uses projections that reflect the most likely (or mid-level) demographic trends; alternative assumptions could be used to develop different projections.

Population Projection Results

Following the methodology and procedure described in the previous section, populations at the county level are projected into 2060. Figure E-4 shows population in 2010 and projected populations in 2020, 2030, 2040, 2050, and 2060. Figure E-5 shows population density in the corresponding years. It seems that both population and population density increase over the years and across the United States. However, these maps do not tell where population growth or decline will occur.

Figure E-6 shows the change in population size, the percentage change in population size, and the change in population density from 2010 to 2060. Population growth areas seem to be concentrated in the border states of the West, South, and East, including Washington, Oregon, California, Arizona, Utah, Colorado, southeast Texas, the Gulf Coast counties, Florida, counties on the East Coast from Florida to Massachusetts, Hawaii, as well as the triangle between Atlanta, Georgia, the Triangle of North Carolina, and Nashville, Tennessee.

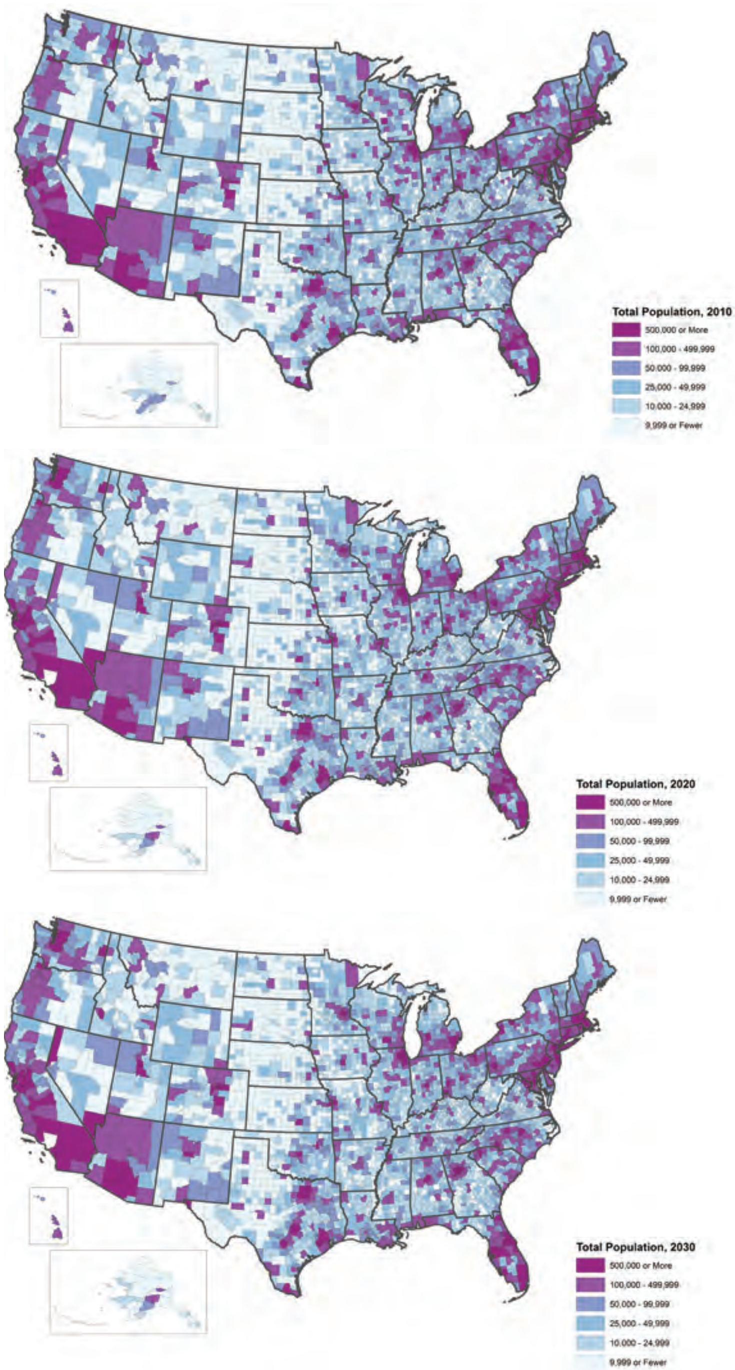


FIGURE E-4 Population in 2010 and projected populations in 2020, 2030, 2040, 2050, and 2060.

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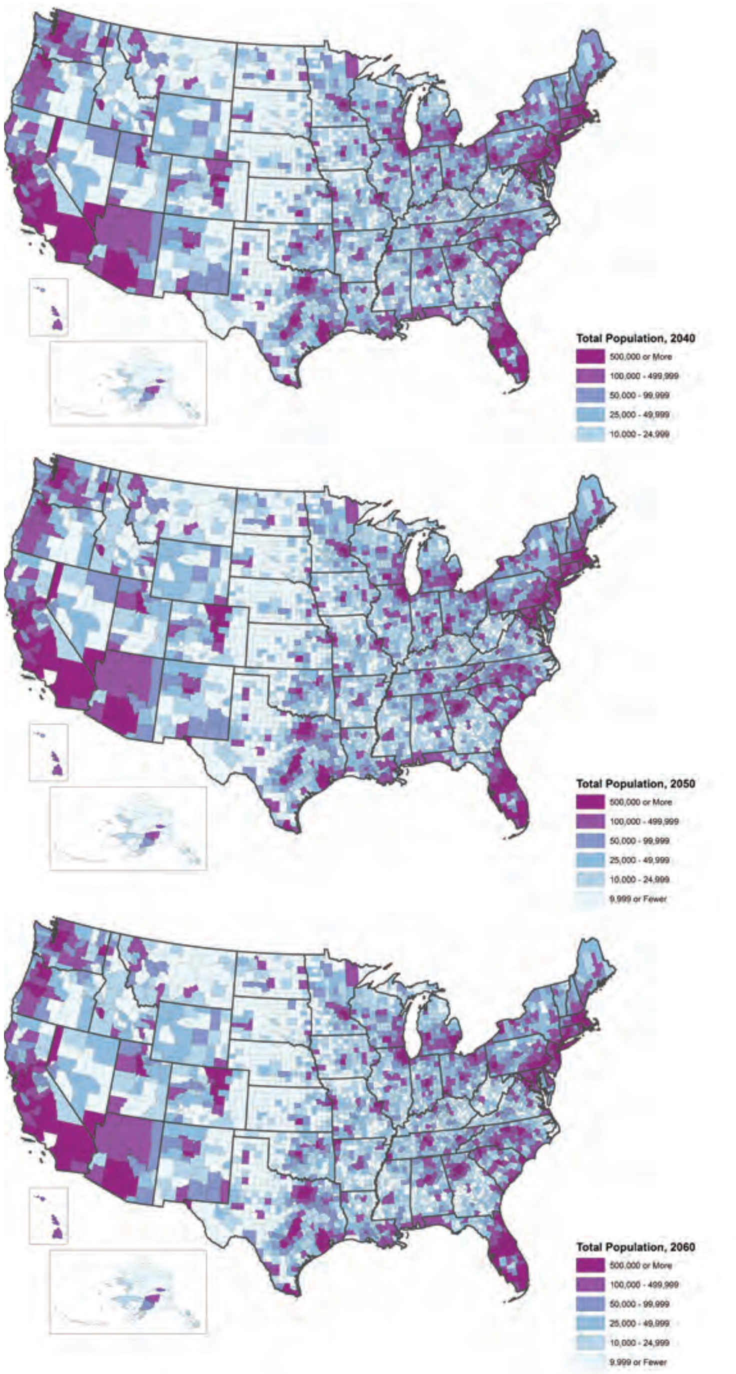

FIGURE E-4 Continued

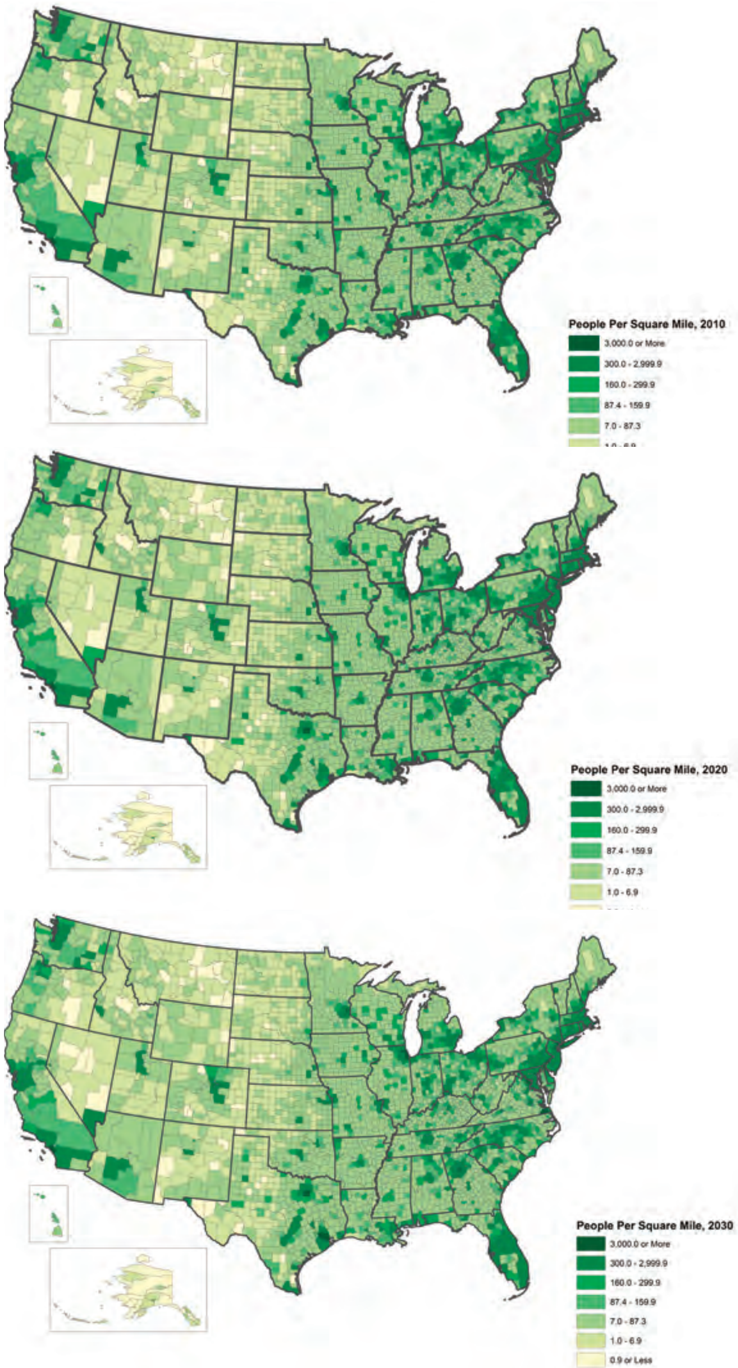

FIGURE E-5 Population density in 2010 and projected population densities in 2020, 2030, 2040, 2050, and 2060.

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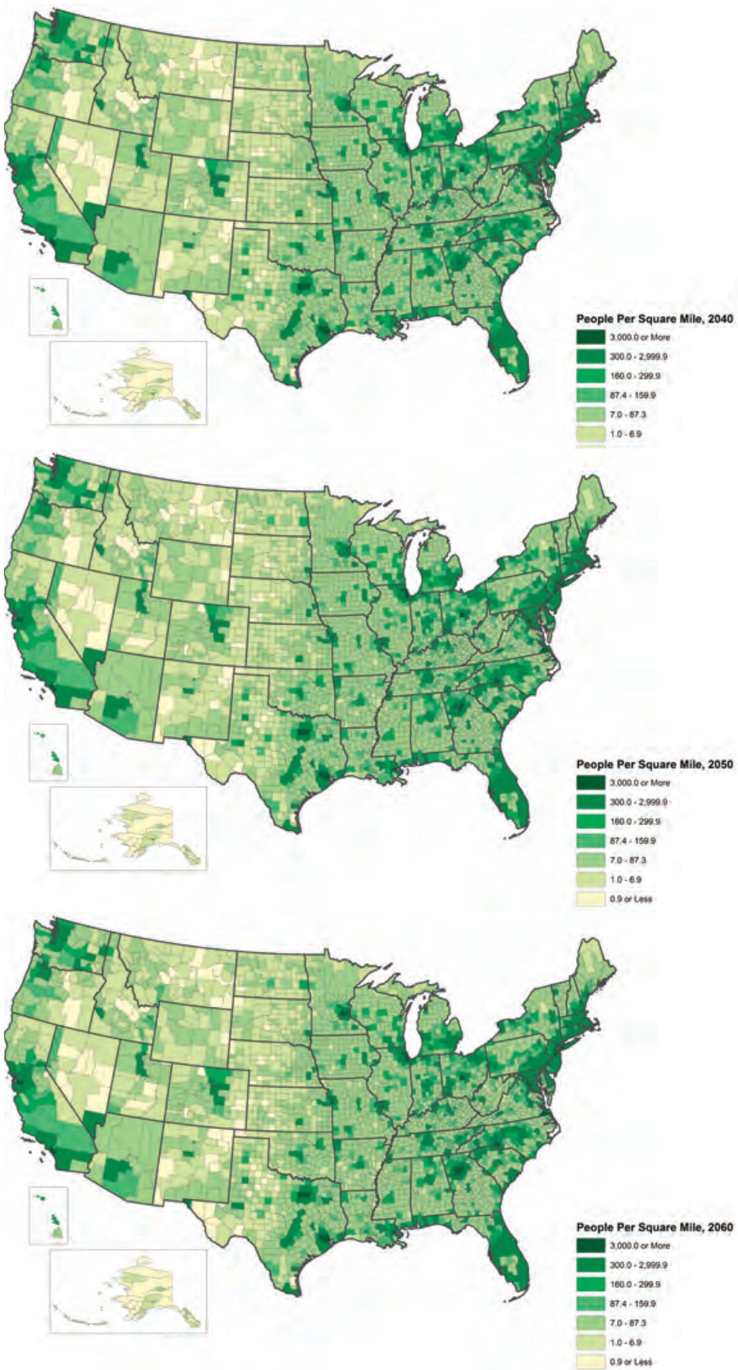

FIGURE E-5 Continued

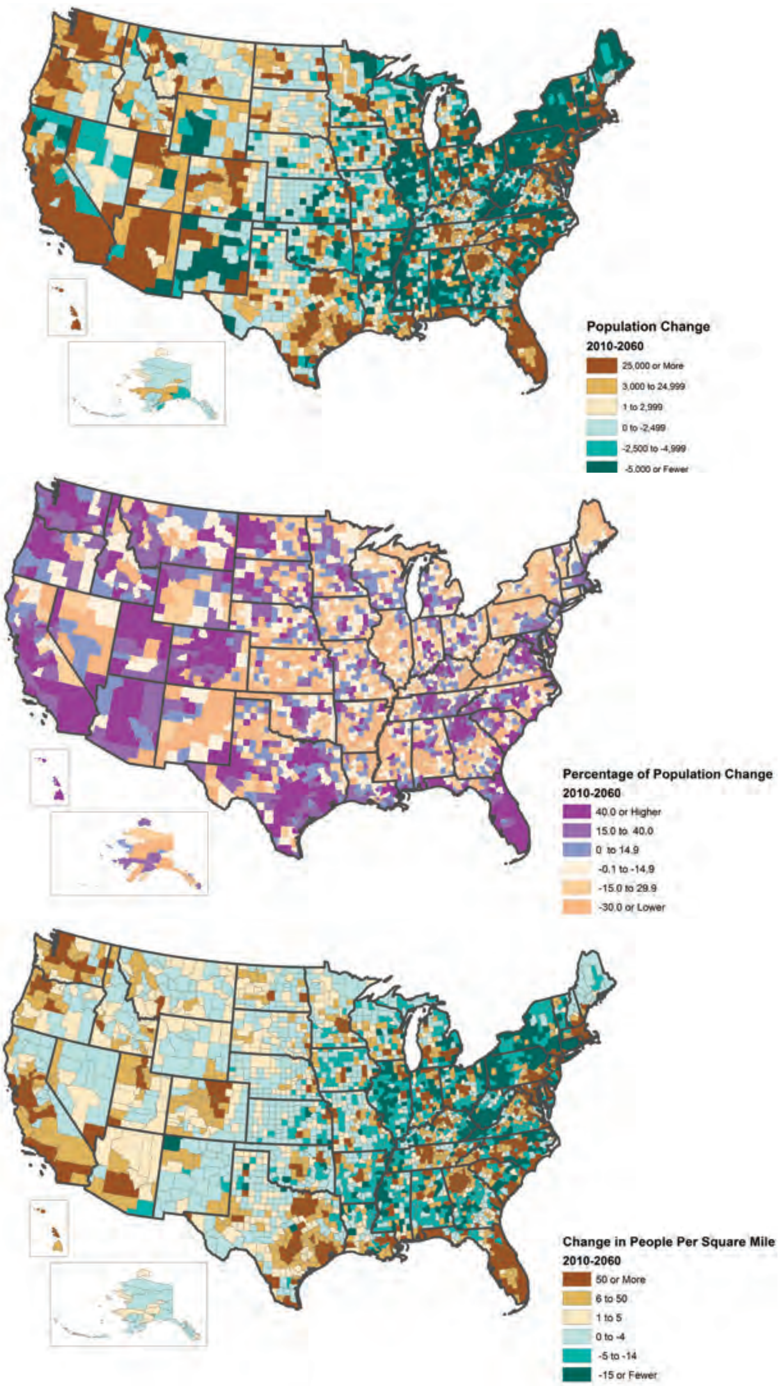

FIGURE E-6 Population change, percentage population change, and population density change, 2010–2060.

There seem to be more counties that will experience population decline. This includes many counties from the northeast corner to the Appalachian region, counties bordering the Great Lakes except Lake Michigan, counties along the Mississippi River, the Deep South states, and Alaska.

IDENTIFYING COUNTIES THAT MAY NEED ADDITIONAL OR LESS INTERSTATE HIGHWAY SYSTEM CAPACITY

Population Change from 2010 to 2060 and Proximity to the Interstate Highway System

As discussed in the review of population–highway dynamics, there is generally a positive relationship between population change and highway needs. To identify counties that may need additional or less Interstate capacity based on the projected population change and proximities to the Interstate System, spatial overlay methods and proximity analysis are used. The assumption here is that population in each county, regardless age, gender, and race/ethnicity, behaves the same in terms of driving over the next 50 years. The potential implications of different demographic groups are discussed in the next section.

Figure E-7 shows the Interstate Highway System and the projected population and population density in 2060. The nodes of the Interstate System are often located in populated or high-density counties. There are 1,444 counties with Interstate highways; these counties are projected to have an average of 247,207 people in 2060. In contrast, there are 1,698 counties without Interstates; these counties are projected to have an average of 34,203 people in 2060. When counties that fall within 20 miles of the Interstate Highway System are included, there are 2,477 counties with an average of 161,821 people in 2060. There are 665 counties that are beyond 20 miles of the Interstate System, with a projected average of 21,372 people in 2060 (see Table E-2 for the descriptive statistics).

Figure E-8 shows projected population change, percentage population change, and population density change from 2010 to 2060 and the Interstate System. The Interstate Highway System passes through both growing counties and declining counties. It is not clear in Figure E-8 how counties with Interstate highways compare to those without.

Counties with Interstate highways are compared to those without by population change from 2010 to 2060 (see Table E-3). The former is projected to gain an average of 68,795 people over the 50 years, whereas the latter is projected to gain an average of only 4,262 people in the same time period. On average, the counties with Interstates are projected to gain 15.51 percent population but the counties without Interstate highways are project to lose 4.28 percent population. Note that the mean of percentage change is calculated as the average of percentage change in each county.

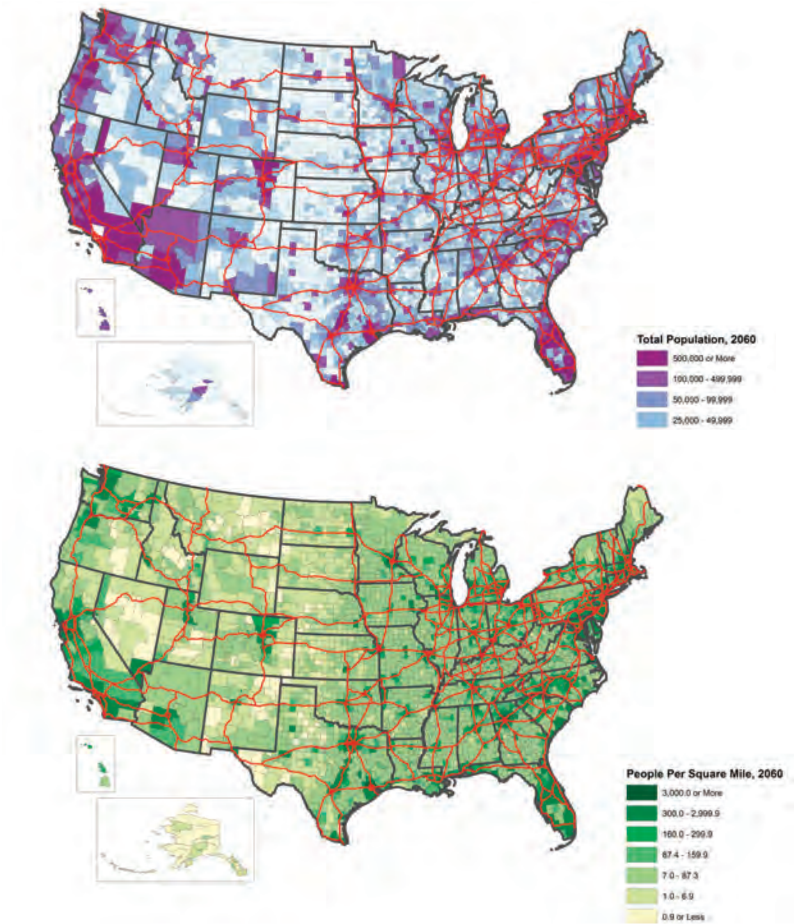

FIGURE E-7 Projected population and population density in 2060 and the Interstate Highway System.

TABLE E-2 Descriptive Statistics of Population and Proximity to the Interstate System in 2060

	N	Mean	SD	Min.	Max.
Counties with Interstate highways	1,444	247,207	637,467	104	12,099,604
Counties without Interstate highways	1,698	34,203	110,294	100	3,263,590
Counties within 20 miles of the Interstate System	2,477	161,821	504,828	104	12,099,604
Counties beyond 20 miles of the Interstate System	665	21,372	40,346	100	477,731

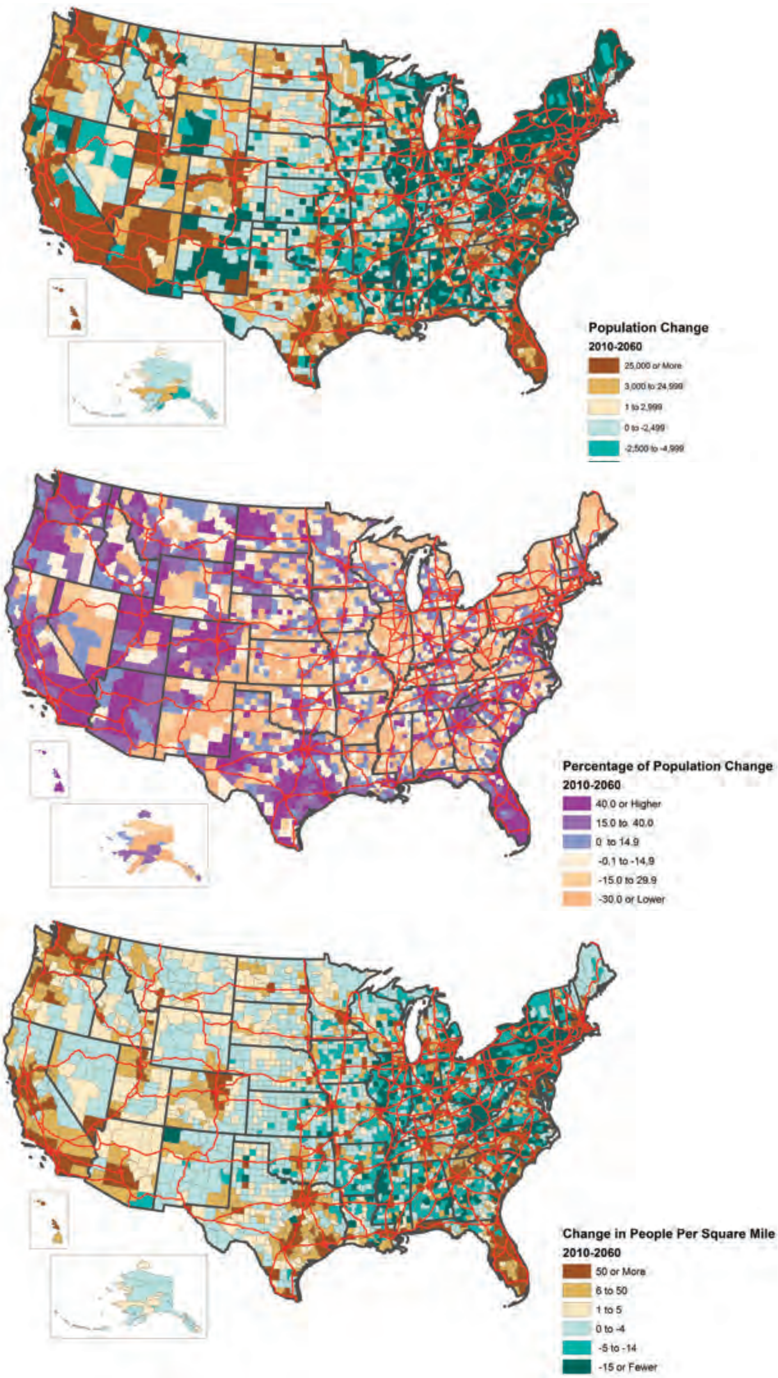

FIGURE E-8 Population change, percentage population change, and population density change, 2010–2060, and the Interstate Highway System.

TABLE E-3 Population Change from 2010 to 2060 and Proximity to the Interstate Highway System

	N	Mean	SD	Min.	Max.
Population change, 2010–2060					
Counties with Interstates	1,444	68,795	244,524	–378,001	3,529,548
Counties without Interstates	1,698	4,262	37,741	–103,561	753,350
Percentage population change, 2010–2060					
Counties with Interstates	1,444	15.51%	46.75%	–79.70%	281.10%
Counties without Interstates	1,698	–4.28%	40.13%	–79.80%	531.40%

The overall population change from 2010 to 2060 in the United States is 38.56 percent for counties with Interstates and 14.23 percent for counties without Interstates.

Counties Along or Close to the Interstate Highway System That May Need Additional or Less Capacity

The counties that are projected to gain or lose population along the Interstate Highway System are highlighted in Figure E-9. The upper map shows the counties that are projected to gain population from 2010 to 2060. These are the counties that may need additional Interstate capacity based on their population projections. The needs are particularly strong in counties along I-5 from Washington to San Diego, California; counties from Los Angeles, California, to Phoenix, Arizona, along I-10; counties from Los Angeles to Albuquerque, New Mexico, along I-40; counties from Los Angeles to Utah along I-15; counties along I-20, I-35, and I-45 spreading from Dallas, Texas; counties along I-20 from San Antonio, Texas, to Pensacola, Florida; the lower Florida counties; counties in the big triangle of Atlanta, Georgia, the Triangle of North Carolina, and Nashville, Tennessee; counties along I-95 from Washington, D.C., to Boston, Massachusetts; and counties from Minneapolis, Minnesota, to Detroit, Michigan, along I-90 and I-94.

The lower map of Figure E-9 shows the counties that are projected to lose population from 2010 to 2060. These are the counties that could need less Interstate capacity based on their population projections. These counties include those from Cleveland, Ohio, to Boston, Massachusetts, along I-90; those from Rockford, Illinois, to Memphis, Tennessee, along I-39 and I-55; and those along I-25 in New Mexico.

Counties that fall within 20 miles of the Interstate System are projected to gain an average of 42,742 people over the 50 years (see Table E-4); these counties are projected to gain an average of 8.11 percent population.

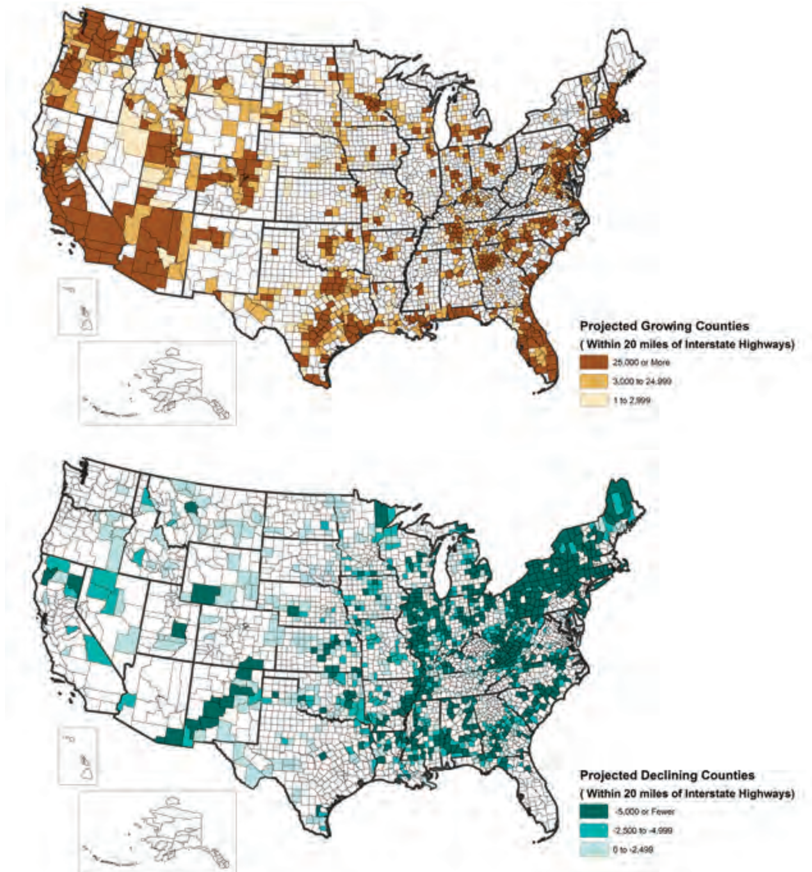

FIGURE E-9 Projected growing or declining counties along the Interstate Highway System.

Counties that fall beyond 20 miles of the Interstate System are projected to gain an average of only 1,060 people; on average these counties are projected to lose 7.45 percent population. Note that the mean percentage change is calculated as the average percentage change in each county. The overall percentage population change from 2010 to 2060 in the United States is 35.89 percent for counties within 20 miles of the Interstate System and 5.22 percent for counties beyond 20 miles of the Interstate Highway System.

The counties that are projected to potentially need additional Interstate capacity based on the 20-mile criterion are highlighted in Figure E-10. Based on their decreased populations, the counties that are projected to potentially need less Interstate capacity based on the 20-mile criterion are highlighted in Figure E-11. Overall, the results are similar to those based

TABLE E-4 Population Change from 2010 to 2060 and Proximity to the Interstate Highway System

	N	Mean	SD	Min.	Max.
Population change 2010–2060					
Counties within 20 miles of the Interstate System	2,477	42,742	191,554	–378,001	3,529,548
Counties beyond 20 miles of the Interstate System	665	1,060	16,661	–103,561	203,613
Percentage population change 2010–2060					
Counties within 20 miles of the Interstate System	2,477	8.11%	44.29%	–79.80%	281.10%
Counties beyond 20 miles of the Interstate System	665	–7.45%	42.67%	–79.60%	531.40%

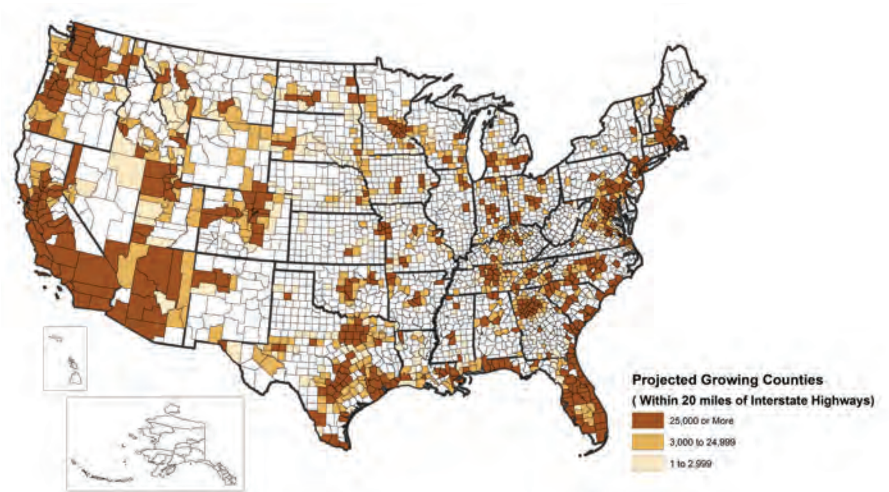

FIGURE E-10 Counties neighboring the Interstate System with projected increasing populations.

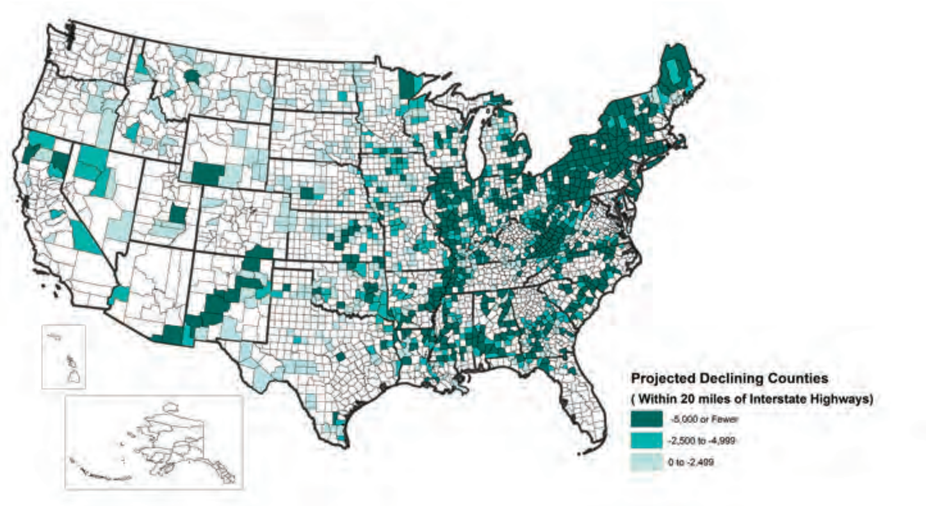

FIGURE E-11 Counties neighboring the Interstate System with projected decreasing populations.

on the with-or-without—Interstate network results, but the former includes more surrounding counties.

Counties Without Interstate Highways But Projected to Experience Rapid Population Growth and Population Density Increase

The counties identified in the previous section either have the Interstate highways or are within 20 miles of the system. The remaining counties of the United States could still have the potential to be provided with a new Interstate highway, if they have high population density and are predicted to experience rapid population growth. To identify these possible counties, two criteria are used. One, they should rank in the top 50 percent among all growing counties as measured by population growth rate. Two, they should rank the top 50 percent among all growing counties as measured by population density increase. Figure E-12 highlights counties that do not have an Interstate highway. These counties are scattered from the northwest corner of Washington to the west of Colorado, from the southeast corner of New Mexico to Houston, Texas, to the tristate counties of Montana and Dakotas, northwest of North Dakota, and to Hawaii.

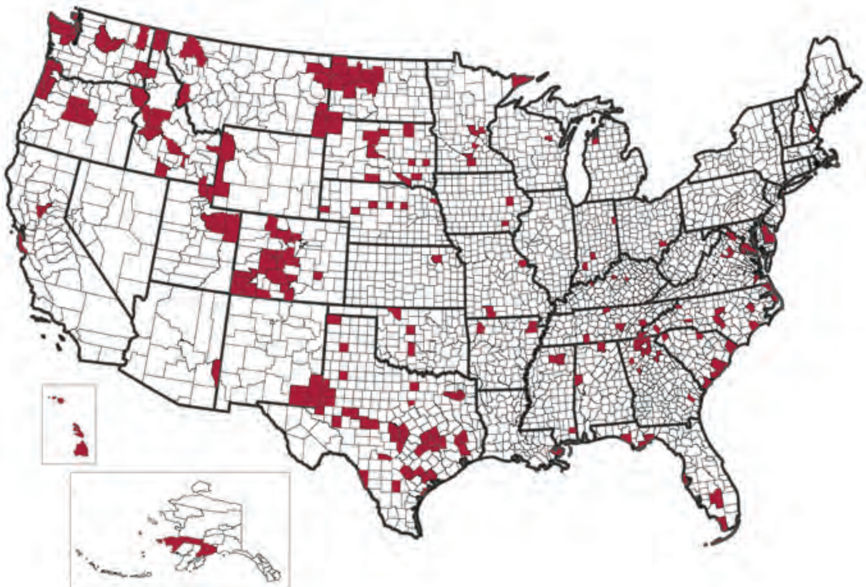

FIGURE E-12 Growing counties that do not have the Interstate highways.
NOTE: The highlighted counties are selected based on both the top 50 percent population growth rate and the top 50 percent population density increase (the difference of population density between 2060 and 2010).

IMPLICATIONS OF AGING POPULATION, MILLENNIALS, IMMIGRANTS, AND TELECOMMUTING

Population Pyramids and Age Variations of Interstate System Users

Demographic characteristics can play a role in travel patterns and the demand for different travel modes. In the United States the number of vehicle-miles traveled (VMT) per person grew until 2007, declined to 2014 (Sivak 2013), and has bounced back since then. The overall long-term growth in miles traveled may be attributed to changing demographics or an improving economy (Zmud et al. 2014). Depending on the amount of driving, the types of preferred transportation, and the reasons for driving, different demographic groups may need Interstates more or less than other demographic groups (Tilley 2017).

To understand the age variations of the Interstate System users, it is helpful to understand the population pyramids of the United States. In 2016, the U.S. population was approximately equally distributed from age 0 to age 60 but declined quickly after that (see Figure E-13). This suggests that the U.S. population is still a relatively "mature" population.

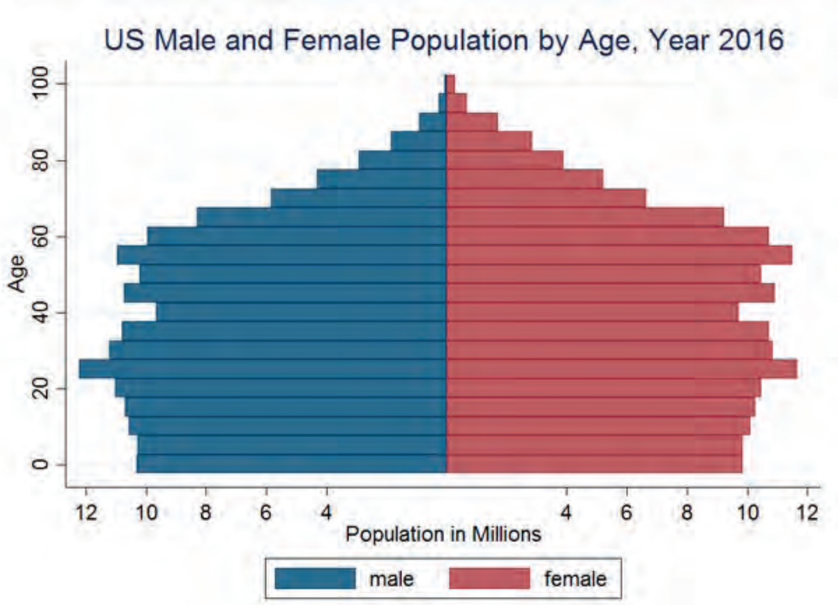

FIGURE E-13 Population pyramid in 2016.

Population pyramids from 2010 to 2060 are illustrated in Figure E-14. Although all age groups are projected to increase over the 50 years, the elderly (age 65 and older) will increase more. This is shown in Figure E-15, where each age group is presented as a percentage of the total population.

The Aging Population and the Baby Boomers

The population of the United States is aging, meaning a larger share of the population is composed of older people. In terms of transportation, one of the most notable cohorts is made up of the baby boomers, those born between 1946 and 1964 (Zmud et al. 2014). This large cohort has now reached retirement and makes up the largest portion of elderly people. Unlike previous cohorts, many baby boomers are choosing to retire in the same place where they lived during their working years and do not plan to give up their driving habits (Alsnih and Hensher 2003). Studies have shown that increasing numbers of older people continue to have driver's licenses and to drive (Sivak and Schoettle 2011a, 2011b; Stokes 2012).

Yet, even with the continued presence of baby boomers on the road, overall older people still tend to drive less than middle-age people. They take fewer daily trips, travel shorter distances, and have shorter travel times than people under age 64 (Collia et al. 2003). While older people may

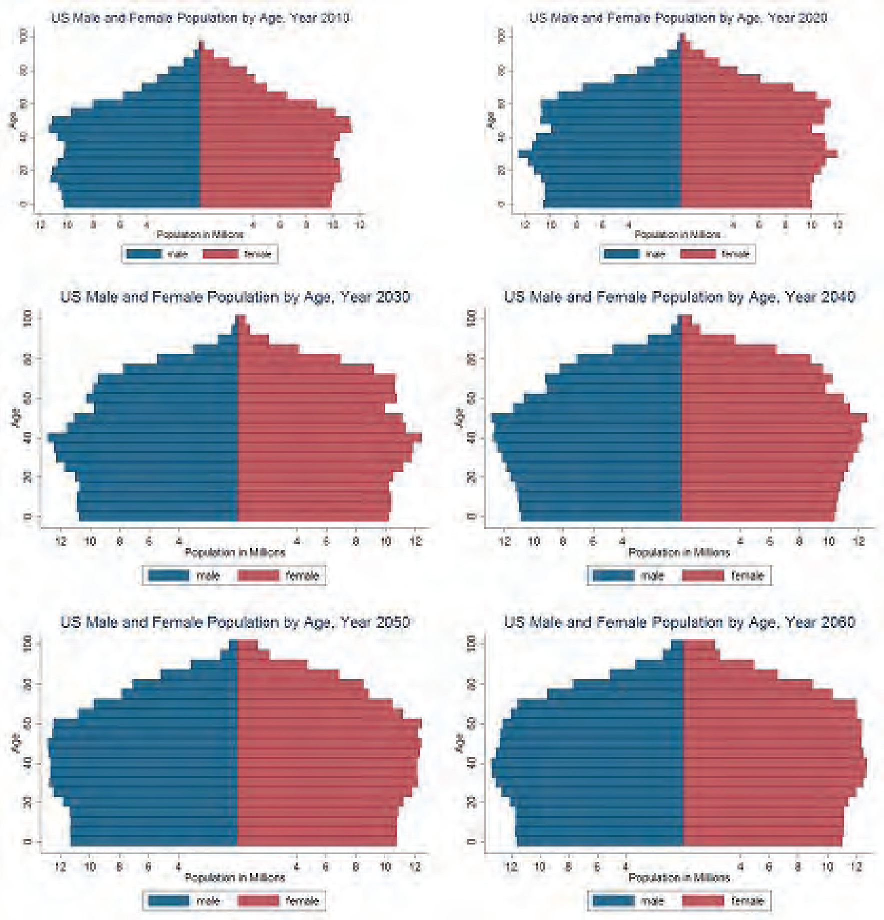

FIGURE E-14 Population pyramids in 2010, 2020, 2030, 2040, 2050, and 2060.

make fewer trips, they often couple multiple destinations within one trip (going to the store, visiting a relative, running an errand, and then returning home) (Alsnih and Hensher 2003). Older people drive at different times than younger people, with much of the older population's driving occurring between the hours of 9:00 a.m. and 4:00 p.m. They cite congestion as a particular driving concern (Collia et al. 2003).

Although older people may not drive as much, they may still require the conveniences of the Interstate System through their use of online and delivery services, which allow them the convenience of shopping without leaving their own homes (Alsnih and Hensher 2003). Older people also prefer to drive (rather than fly or take a train) when going on long-distance

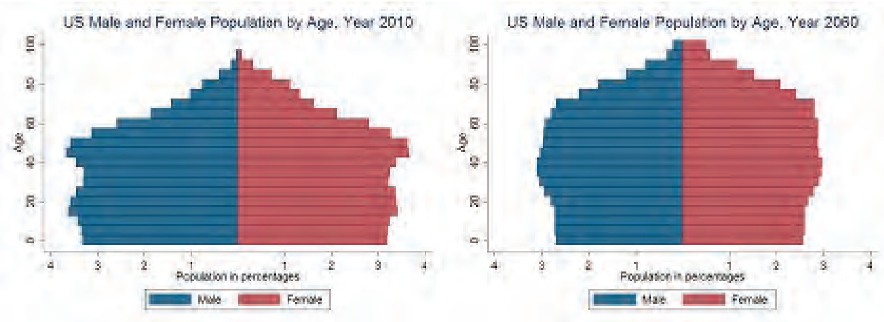

FIGURE E-15 Population pyramids in percentages in 2010 and 2060.

trips, and they drive more miles on these trips than younger people (Collia et al. 2003).

Figure E-16 shows the distribution of the aging population in 2015. As we look to the future, the population of older people (age 65 and older) will begin to rapidly increase (see Figure E-17). We expect that between 2010 and 2060 the share of people in this age group will jump from 13 percent of the population to more than 23 percent. In raw numbers, the aging population will double from just more than 40 million people to more than 98 million. Most notably, the share of the oldest older population, those over 80 years old, will greatly increase. In 2010 the 80 and older population was 11 million people, but it is projected that by 2060 it will be almost 40 million.

Baby boomers, the cohort of babies born after World War II, is a generation of adults now entering retirement age. For this analysis, baby boomers comprise those born between 1946 and 1964. In 2010, the 81 million baby boomers made up 26 percent of the population (see Figure E-18). In the coming decades, as they age and eventually die, the population of baby boomers is expected to decrease, as will their share of the population. By 2060, all baby boomers are expected to be over age 95 and will make up less than 1 percent of the total population.

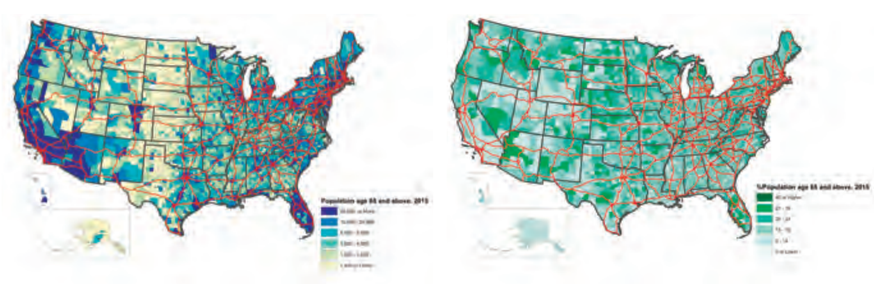

FIGURE E-16 Distribution of aging population in 2015 at the county level.

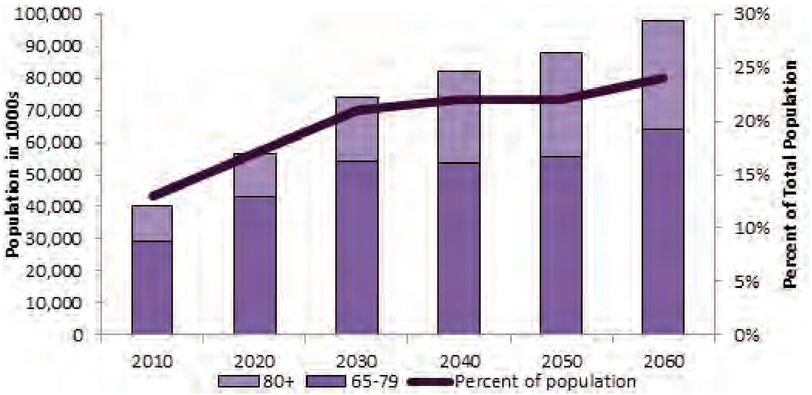

FIGURE E-17 Projected aging population (age 65+) in the United States, 2010–2060.

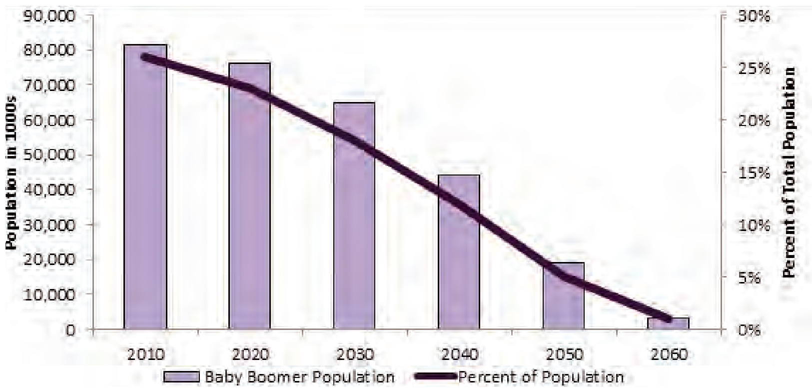

FIGURE E-18 Projected population of baby boomers (born 1945–1964) in the United States, 2010–2060.

The Young Population and the Millennials

Interestingly, fewer young people are obtaining their driver's licenses than in previous generations. Although 77 percent of 18-year-olds in 1990 had a driver's license, a study in 2013 found that only 54 percent of 18-year-olds did (Research Triangle Institute 1991; Tefft et al. 2013). It is possible that these young people weigh the benefits of cost, convenience, and the environment when making driving decisions.

Following the millennial generation, a new cohort of the population is entering the age requirements permitting them to drive. Millennials, the generation of younger adults born in the 1980s and 1990s (Zmud et al.

2014), are a popular subset of the population for study. Millennials are more likely to want to live in cities and to use public transportation for their commutes than older adults (Belden Russonello Strategists 2013; Ralph et al. 2016; Zmud et al. 2014). Millennials may demand less from the Interstate System because of their mix of different modes of transportation, their urban living, and their environmental concerns (Sakaria and Stehfest 2016). Cost is the primary driver behind millennial transportation choices.

The distribution of the young population in 2015 is shown in Figure E-19. The population of young people, those between ages 15 and 34, will remain fairly stable over time (see Figure E-20). While the number of young people is expected to increase from 84 million people in 2010 to almost 98 million in 2060, the share of young people in the overall population will decrease from 27 percent to 23 percent. The shares of young people by different age categories, such as 15–19, 20–24, and 25–34, are expected to remain fairly consistent across decades.

For this analysis, the millennial cohort comprises those born between 1982 and 1996 (Pew Research Center 2013). Millennials in 2010 made up almost 21 percent of the total population, when they were between the ages of 15 and 29. Although the number of millennials remains fairly stable over time, the share of the population occupied by millennials is expected to decrease over time. By 2060, when millennials are between the ages of 65 and 79, they are expected to make up 15 percent of the total population (see Figure E-21).

Immigrants

About 12.6 percent of the U.S. population is foreign born (Chatman and Klein 2009). Overall, it appears that immigrants are less likely than native-born Americans to drive in private cars and are more likely to use forms of public transportation available in cities. Zmud and colleagues (2014) found that foreign-born Hispanic and Asian workers used public transportation twice as much as native-born workers, and Chatman and Klein (2009) found that foreign-born workers were about three times more likely to use public transportation than native-born workers. Even when traveling between cities, private shared transportation such as greyhound buses are used by immigrants at higher rates (Chatman and Klein 2009). It is possible that with the emergence of new immigrant destinations in smaller cities and rural communities, immigrant use of private cars for transportation and use of the Interstate System for both daily and long-distance trips may increase (Tal and Handy 2010).

The distribution of immigrants in 2015 is shown in Figure E-22. The population of those born outside the United States is projected to increase steadily between 2010 and 2060 (see Figure E-23). Additionally, the

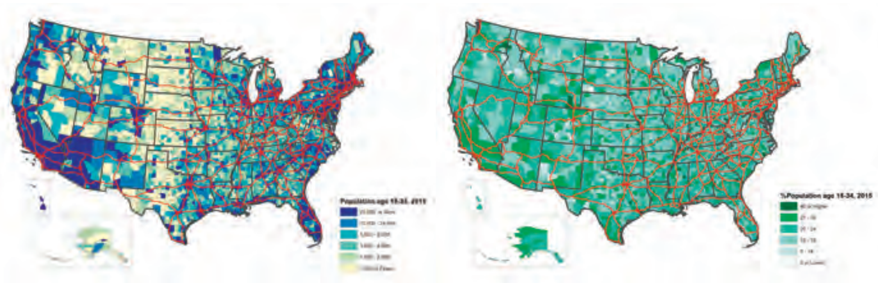

FIGURE E-19 Distribution of the young population in 2015 at the county level.

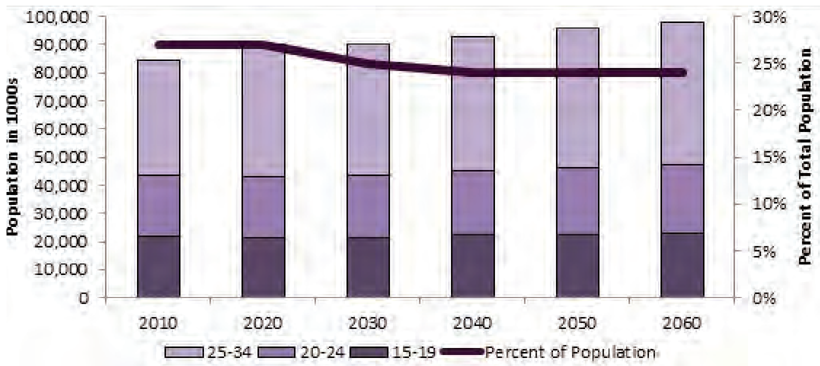

FIGURE E-20 Projected young population (ages 15–34) in the United States, 2010–2060.

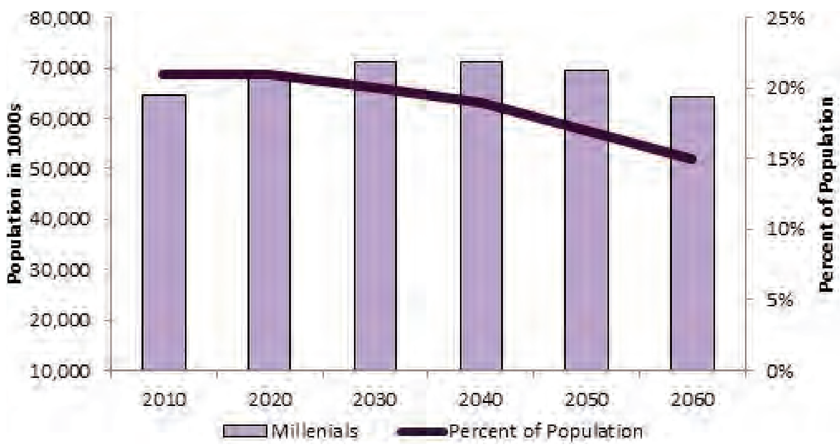

FIGURE E-21 Projected population of millennials (born 1982–1996) in the United States, 2010–2060.

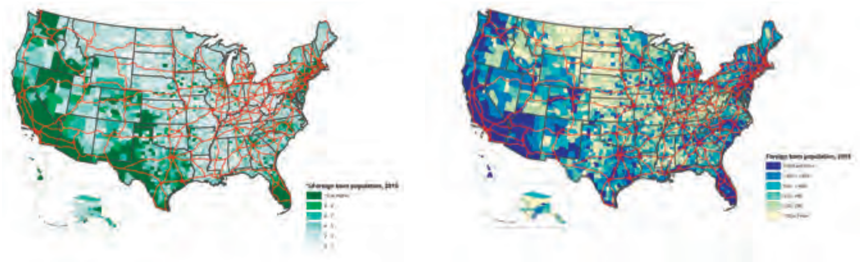

FIGURE E-22 Distribution of immigrants in 2015 at the county level.

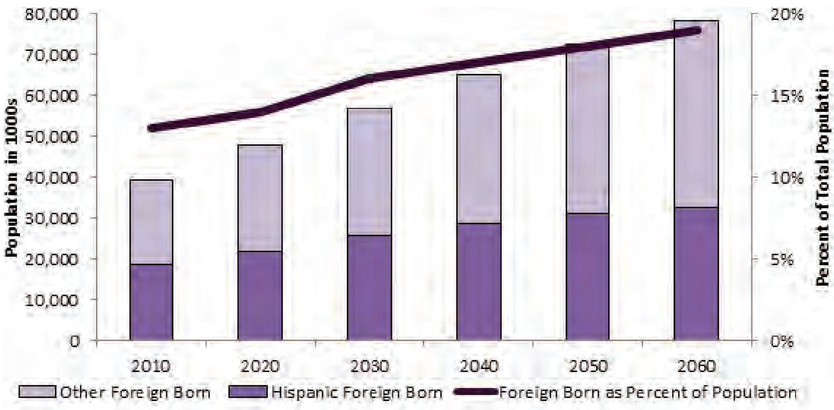

FIGURE E-23 Projected population of immigrants in the United States, 2010–2060.

percentage of the population comprising those born outside the country is projected to increase from 13 to 19 percent. Among the foreign-born population, Hispanics make up the largest racial/ethnic category. In 2010, almost half the foreign-born population was Hispanic. However, the portion of the foreign-born population comprising people who are not Hispanic is projected to increase over time.

Telecommuting

Adults, young and old, are now more connected to technology than ever. Ninety-one percent of Americans own a cell phone, and more than half own a smartphone (Pew Research Center 2013). Young people who grew up with the Internet and other forms of technology are now of driving and working age. Although some believed that technology might decrease the need for travel, particularly reducing work commutes through the development of telecommuting technology, the impact has been mixed (Zmud et al. 2014). Issues of broadband access, particularly in rural communities, and Internet connectivity through devices other than computers may still necessitate in-person working. However, expansion of new forms of technology may change the needs for interstate and highway transportation in the future for both the commutes of people and the delivery of goods.

Telecommuting is the act of doing work at home. With e-mail, social media, and other forms of remote working, many people have already incorporated some elements of telecommuting into their jobs. Jobs that formally incorporate telecommuting may allow employees to work from home 1 day a week or may allow workers to complete all work remotely. In 2010, management, business, financial, professional, and related occupations had the largest percentage of their workforce engaging in some amount of telecommuting, with almost 33 percent (see Figure E-24). Unsurprisingly, those who worked in production occupations had the smallest portion of their workforce working from home, and other occupations that require hands-on or face-to-face service also had small portions of their workforces engaging in remote work. It is likely that certain occupations may be able to greatly increase their telecommuting workforce in the future but that other occupations will not.

As a final note, it should be emphasized that population is only one factor associated with VMT and Interstate System demands. VMT is also related to employment growth, GDP, and GDP per capita, as shown in Figure E-25. These factors should be considered when predicting future Interstate System demands.

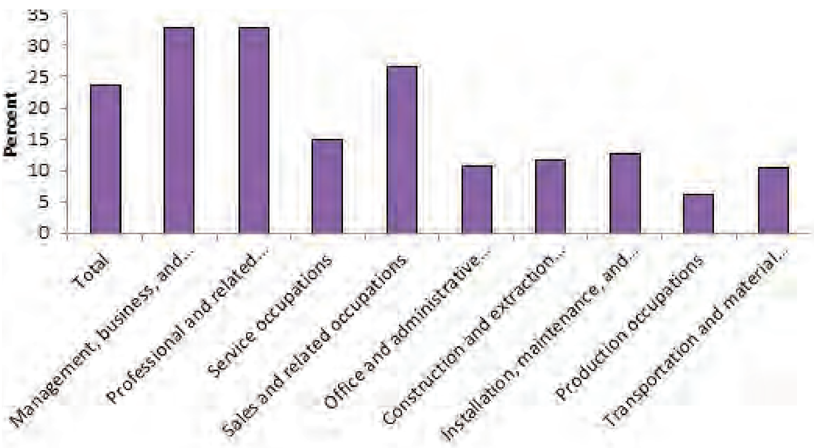

FIGURE E-24 Percentage of workers doing some or all of their work from home in the United States, 2010.

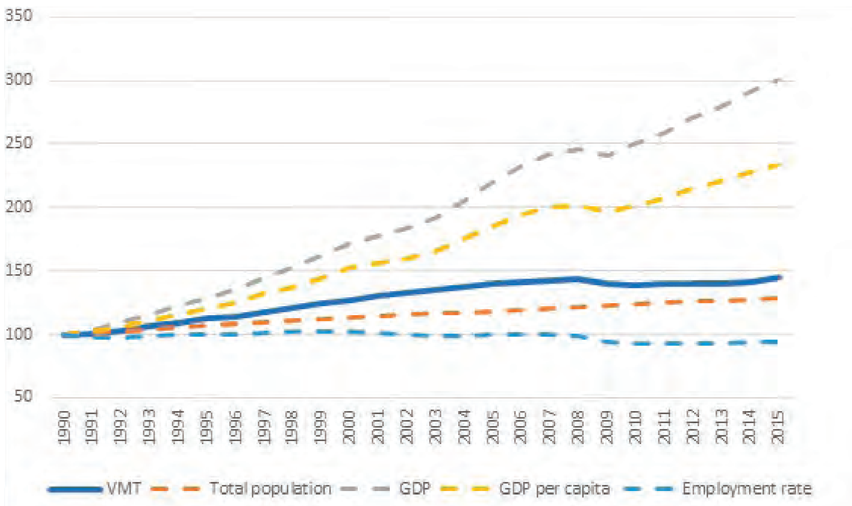

FIGURE E-25 Vehicle-miles traveled, total population, GDP, GDP per capita, and employment in the United States, 1990–2015.
NOTE: All numbers are standardized (year 1990 = 100) to better visualize the association between their corresponding lines.

CONCLUSIONS

Population growth demands higher Interstate System capacity. To upgrade and restore the Interstate Highway System as a premier system for the 21st century, demographic forecasting is a must before any transportation planning and decision activities. This appendix provides population projections into 2060 at the county level for the entire United States using cohort-component methods. The United States is projected to experience population growth across all age groups over the next 50 years. The projected growth, however, varies across the entire United States. Population growth areas seem to be concentrated in the border states of the West, South, and East, as well as the triangle between Atlanta, Georgia, the Triangle of North Carolina, and Nashville, Tennessee. Population decline areas include many counties from the northeast corner to the Appalachian region, counties bordering the five Great Lakes except Lake Michigan, counties along the Mississippi River, the Deep South states, and Alaska.

This appendix also identifies the counties that may need additional or less Interstate capacity based on the projected population change and proximities to Interstate highways by using spatial overlay methods and proximity analysis. Only the counties that fall within 20 miles of existing

Interstate highway are included in the analysis. The areas that may need additional Interstate capacity, based on their population projections, are particularly strong in counties along I-5 from Washington to San Diego, California; counties from Los Angeles, California, to Phoenix, Arizona, along I-10; counties from Los Angeles to Albuquerque, New Mexico, along I-40; counties from Los Angeles to Utah along I-15; counties along I-20, I-35, and I-45 spreading from Dallas, Texas; counties along I-20 from San Antonio, Texas, to Pensacola, Florida; the lower Florida counties; counties in the big triangle of Atlanta, Georgia, the Triangle of North Carolina, and Nashville, Tennessee; counties along I-95 from Washington, D.C., to Boston, Massachusetts; and counties from Minneapolis, Minnesota, to Detroit, Michigan, along I-90 and I-94. The counties that may need less Interstate System capacity based on their population projections include those from Cleveland, Ohio, to Boston, Massachusetts, along I-90; those from Rockford, Illinois, to Memphis, Tennessee, along I-39 and I-55; and those along I-25 in New Mexico.

This appendix also identifies the counties with high population density but without Interstates that are predicted to experience rapid population growth because these counties could still have a potential to be invested with a new Interstate highway or corridor. These counties are scattered from the northwest corner of Washington to the west of Colorado; from the southeast corner of New Mexico to Houston, Texas; the tristate counties of Montana and the Dakotas; northwest of North Dakota; and Hawaii.

Note that the Interstate System demands also vary by demographic groups. The U.S. population is aging quickly and the percentage of the aging population is rising, from 13 percent of the total population in 2010 to 23 percent in 2060. Both the baby boomers and the millennials will have a declining share of the total population. Immigrants are projected to increase from about 13 percent in 2010 to 20 percent in 2060. Telecommuting could affect the usage of the Interstate Highway System as well.

That said, future work could provide population projections for these specific demographic groups and for finer geographic scales. For example, population projections by age and projections of immigrants at the county level could provide useful information for the local decision makers. Population projection at subcounty levels could be particularly useful for metropolitan areas, where the Interstate Highway System needs could vary greatly. For example, the Interstate System is seen as a disamenity to immediate neighborhoods but as an amenity (because of accessibility) to neighborhoods just a few blocks away. Producing rigorous population projections by different demographic groups and at finer scales could provide more useful information for decision makers and policy makers in better deciding where to expand or invest in the Interstate Highway System.

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Abbreviations

DOT	Department of Transportation
FHWA	Federal Highway Administration
U.S. DOT	U.S. Department of Transportation

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Appendix F

Connected and Automated Vehicle Technology Impacts on Future Interstate Highway System

Steven E. Shladover

EXECUTIVE SUMMARY

This appendix provides an overview of the implications that development and deployment of connected and automated vehicle (CAV) technology could have for the future of the Interstate Highway System. It begins with an introduction describing the range of connected vehicle (CV) technologies and applications and of automated vehicle (AV) alternatives. The AV alternatives are characterized on the basis of their level of automation, whether their operations are autonomous or cooperative, and on the operational design domains (ODDs) within which they are capable of operating at any stated level of automation. The levels of automation are defined based on the SAE classifications that specify the relative roles of the driver and the driving automation system. The ODD represents the range of roadway classifications, speeds, traffic, and weather conditions in which any specific AV system is able to operate, and when that is combined with the levels of automation, it represents the great diversity of AV system concepts of operation and capabilities.

Many aspects of the technological development and public implementation of the CAV technologies are shown to be highly uncertain. Because CAV systems integrate elements from the information technology, vehicle technology, and infrastructure industries, the implementation of these systems is conditioned by the contrasts in the timescales within which these industries evolve. The real-world implementation times are much more likely to be governed by the slowest of these than by the fastest. The deployment patterns are also likely to vary substantially among regions of the country, and so a single national deployment profile cannot be assumed. Given these uncertainties, decisions about future roadway infrastructure should not be finely tuned to specific assumed technology deployment schedules, but rather need to be robust with respect to a wide range of possible CAV deployment patterns.

The CAV technologies will influence both the supply and demand sides of the transportation system, with somewhat different implications for passenger and freight transport. The expected influences of CAV (and related information technologies) on passenger and freight travel demand are described separately. There will be both positive and negative influences on the number of trips to be taken, as well as on the character of the trips, and because of this diversity of impacts, it is very difficult to make reliable predictions about the net impacts. The influences of CAV technologies on the supply side of road transportation operations are also discussed, in this case with somewhat less uncertainty based on results from early technological experiments that show the potential to increase highway capacity and improve traffic flow dynamics.

The appendix concludes with estimates of realistic expectations for the changes that CAV technologies could make to interstate highway operations within the next 10, 20, and 50 years. At the 10-year horizon, the early impacts of CV technology should be felt, but that will be too early to see significant impacts from AV technology. By the 20-year point, the lower-level AV technologies should be in use on enough vehicles that their impacts should become evident, but these will still not produce revolutionary changes to the design or operation of the Interstate Highway System. The 50-year mark is more challenging to predict because of the many uncertainties involving the rate of maturation of the AV technologies and the extent to which they will be embraced by the public for widespread use. This means that 50 years from now the transportation system could on the one hand be only modestly different from today or it could on the other hand be largely transformed into something more highly automated and connected than today's system.

INTRODUCTION OF CONNECTED AND AUTOMATED VEHICLE TECHNOLOGIES

Modern information technology has been gradually entering the road transportation system over the past two decades under the label of intelligent transportation systems (ITSs). These represent combinations of sensor systems (on both vehicles and infrastructure), computer hardware and software to process the sensor data and make decisions, communication systems to exchange information among vehicles and between vehicles and the roadway infrastructure, actuators to command vehicle motion changes;

and human–machine interfaces to exchange information with drivers and travelers.

In recent years, attention has been focused specifically on CV systems and AV systems, and on their combination (CAV systems). The CV systems exchange information among vehicles and between vehicles and the roadway infrastructure, while the AV systems relieve drivers of some or all of the tasks associated with controlling the motions of vehicles. The specific CV and AV technologies are introduced in this section to provide a foundation for the discussion that follows about their implications for the future of the Interstate Highway System.

Connected Vehicle Systems

For at least the past 15 years, the primary focus of the U.S. Department of Transportation (U.S. DOT) ITS program has been on CV systems, although this has been done under several different labels (Intelligent Vehicle Initiative, IntelliDrive, and now Connected Vehicles). The basic concept is largely the same, that wireless communications among vehicles (vehicle-to-vehicle [V2V]) and between vehicles and the roadway infrastructure (vehicle-to-infrastructure [V2I] and infrastructure-to-vehicle [I2V]) and between vehicles and other entities such as pedestrians and bicyclists (vehicle-to-everything [V2X]) can enable the transportation system to function more effectively as an integrated system.

The primary emphasis of most of these efforts has been on improving safety by use of one specific wireless technology, 5.9-GHz dedicated short-range communication (DSRC). However, that scope has broadened considerably to encompass other wireless technologies and improvements in other transportation system measures of effectiveness.

V2V connectivity can enable applications such as

- Cooperative collision warnings and hazard alerts, as tested in the Safety Pilot Model Deployment;
- Cooperative collision mitigation or avoidance, incorporating active braking;
- Cooperative adaptive cruise control, with tighter vehicle following control than conventional adaptive cruise control and enhanced traffic flow stability;
- Close-formation automated platooning, enabling aerodynamic drafting and lane capacity increases;
- Automated maneuver negotiation at merging locations or intersections; and
- Transit bus connection protection.

All but the last of these are time-critical and safety-critical applications that need very low-latency and high-reliability communications. For most of these applications, the communicated data are used to augment the data acquired by onboard remote sensors, which remain the primary source of data about time-critical and safety-critical conditions.

I2V connectivity can provide

- Traffic signal status information in real time for in-vehicle display, signal violation warning, or green wave speed advisories to drivers;
- Traffic and weather condition information and real-time routing advisories to drivers;
- Fleet management functions of vehicle routing and scheduling;
- Access control to closed facilities;
- Variable speed limits and advisories directly to drivers or their vehicles (I2V cooperative adaptive cruise control);
- End-of-queue warnings; and
- Active support for lane guidance.

V2I connectivity can enable

- Vehicle probe data applications providing detailed traffic information (speed, volume, travel time, queue length, stops) or road surface condition information (pavement roughness or slippery conditions);
- Mayday and concierge services (such as OnStar);
- Electronic toll collection and parking payments;
- Traffic signal priority requests; and
- Vehicle status information for fleet management (especially for transit and trucking fleets).

CVs can rely on a variety of wireless communication technologies for their connectivity. In the earlier years of the Vehicle-Infrastructure Integration (VII) program within the U.S. DOT, attention was focused entirely on 5.9-GHz DSRC technology, since that special-purpose wireless technology was designed specifically for the mobile environment and it was thought that it could serve all mobile communication needs. Since then, it has become evident that a wider range of wireless technologies, with differing strengths and weaknesses, could be used to support ITS applications:

- The 5.9-GHz DSRC is a special WiFi-like technology designed for road transportation applications, but using a licensed and protected spectrum. It has a unique ability to support time-critical and safety-critical messages over a limited range. Since it is specific to the road transportation environment, it benefits less from commercial developments and economies of scale than some of the other technologies. The National Highway Traffic Safety Administration (NHTSA) has released a Notice of Proposed Rulemaking to create a new Federal Motor Vehicle Safety Standard (FMVSS) 150 that would require all new vehicles to be equipped with this radio technology starting in the early 2020s so that the information that they broadcast periodically (10 times per second) can be used by other vehicles to predict potential crashes and alert drivers to avoid those crashes (NHTSA 2017).

- WiFi can be used, where available, to support some ITS functions, but it has relatively long connection latency and is susceptible to delays and packet losses when the channel is congested, and so its dependability is inadequate for critical information.
- Cellular communications include 4G LTE and WiMAX technologies and their future generations, generally termed 5G cellular. The infrastructure side of the current generation of this system is essentially ubiquitous in built-up areas, and so it does not need to be provided by public agencies, but users on both the vehicle and infrastructure sides need to pay the network operators for data usage. The development of 5G cellular is under way, but its real capabilities are not yet clearly defined and its deployment timescale remains uncertain.
- Satellite communication systems can be used in remote areas that lack cellular service, but they face significant cost, bandwidth, and latency limitations, which mean that they are not suitable for all applications.
- Bluetooth can provide only very short-range and low-bandwidth service to support some applications.

State and local transportation agency issues come to the forefront for DSRC rather than the other alternatives because the implementation of the infrastructure elements of this system will most likely depend on actions by these agencies (at least providing access to their field devices and probably funding as well). DSRC is needed for the V2V safety and I2V intersection safety applications, and so these are the ones that will require involvement by the transportation agencies.

The transportation agencies will also need to be involved in the I2V and V2I applications that support or influence transportation system management, regardless of the wireless technology that is selected. As the owners and operators of the transportation management centers, they will be the users and, in many cases, the providers of the data, so they need to be actively engaged in the development, deployment, maintenance, and operation of these information systems.

Automated Vehicle Systems

AV systems have had a considerably longer and more irregular history than CV systems, with many ups and downs since the concept of road vehicle automation was introduced by Norman Bel Geddes in the General Motors Futurama exhibit at the 1939–1940 New York World's Fair (Bel Geddes 1940). The first wave of research and development on automated road vehicles was undertaken by General Motors and RCA beginning in the 1950s (Bender 1991), and the second wave was led by Robert Fenton at The Ohio State University from 1964 to 1980 (Fenton and Mayhan 1991). The third wave was initiated with the founding of the PATH Program by Caltrans and the University of California in 1986 (Shladover 1990), reached a climax with the research and demonstration work of the National Automated Highway Systems Consortium from 1994 to 1998 (Rillings 1997), and continued until 2003, when Caltrans and PATH did joint demonstrations of automated bus platoons and truck platoons. Parallel activities were initiated in Europe and Japan in the mid-1980s, including pioneering research on the application of video image processing for driving scene recognition by Ernst Dickmanns (2002) and the wide-ranging research and demonstration work conducted under the PROMETHEUS program in Europe (Glathe 1994) and the Super-Smart Vehicle Systems (SSVS) program in Japan (Tsugawa et al. 1992). The fourth wave, which continues today, began with the DARPA Challenges in the 2004–2007 period and the ensuing work by Google, with its first public announcement in 2010. There have been many journalistic reviews of the hype surrounding this wave but relatively few sober assessments (Anderson et al. 2016; Shladover 2016).

One of the primary current challenges in the AV domain is managing the unrealistic expectations of the general public, elected officials, and some transportation professionals. Media coverage and Internet chatter has misled many people about what capabilities can be achieved within the coming years and decades, and the imprecise and inaccurate vocabulary used to discuss AVs adds to the confusion. The words "driverless," "self-driving," and "autonomous" are frequently applied to systems that still depend very heavily on human engagement in the driving task, blurring important distinctions among the capabilities of different systems. The companies that are active in this space are competing strongly for media attention and public image, and so they have been making misleading statements and encouraging media people to extrapolate beyond the reality of what is actually likely to be deployed for public use.

It is important to begin consideration of AVs by recognizing the great diversity of AV applications and concepts of operation and the large differences in when they will become available for use by the public. The highest levels of automation have the potential to revolutionize the transportation system in a variety of ways, but there are large uncertainties about how far in the future those will become available. On the other hand, the lower levels of automation are imminent and transportation officials need to understand their limitations and their implications for the transportation system.

There are three important dimensions of classification of AV systems:

- Level of automation capability,
- Distinction between autonomous (unconnected) and cooperative (connected) implementations, and
- ODD.

Although most of the earliest automation systems to become available, which provide low levels of automation of driving functions, are autonomous, over the longer term as higher levels of automation are developed, it will be increasingly important for the automation systems to be cooperative (cooperation among vehicles and between vehicles and the roadway infrastructure) in order to produce transportation system benefits. The ODD is the combination of specific conditions under which a driving automation system is designed to function, including driving modes, roadway types, traffic conditions, speed range, geographic locations (boundaries of digital maps), weather and lighting conditions, and availability of necessary supporting infrastructure features including condition of pavement markings and signage, and so forth.

SAE International (formerly the Society of Automotive Engineers) has developed a five-level classification of automated driving systems, which is very useful for distinguishing the capabilities that will be available at each level (SAE International 2016). Without belaboring the fine points of the definitions that distinguish the five levels from each other, Table F-1 lists examples of the types of systems that would fit within each level and the roles that the driver would have with each of these systems.

The transportation system impacts of these different levels of driving automation system will differ greatly, and so it is important to consider them separately. It is also vital for transportation agency decision makers to make their decisions based on realistic predictions of the timing of the availability of these varying levels of automation.

Level 1 driver assistance systems are already on the market on a variety of vehicles, although they still represent a small fraction of the number of vehicles sold. Adaptive cruise control (ACC), the most important Level 1 system, was first introduced on a production car in Japan in 1995 and first available in the United States in 2000, but it is still not in widespread use, even though this is a feature that is regarded very favorably by people who have used it. Wayland (2015) reported that ACC was installed on 2.2 percent of new vehicles worldwide in 2014, and that number was projected to

TABLE F-1 Summary Descriptions of SAE Levels of Automation

Level	Example Systems	Driver Roles
1	Adaptive cruise control OR lane-keeping assistance	Must drive *other* function and monitor driving environment
2	Adaptive cruise control AND lane-keeping assistance Traffic Jam Assist for freeway (Mercedes, Tesla, Infiniti, Volvo, and so forth) Parking with external supervision	Must monitor driving environment (system nags driver or deactivates itself to try to ensure this)
3	Traffic jam pilot	May read a book, text or Web surf, but be prepared to intervene when needed
4	Highway driving pilot Closed campus "driverless" shuttle "Driverless" valet parking in garage	May sleep, and system can revert to minimum risk condition if needed
5	Ubiquitous automated taxi (even for children) Ubiquitous car-share repositioning system	Can operate anywhere, with no driver needed

increase to only 7.2 percent by 2020. Level 2 partial automation systems have recently been introduced on high-end vehicles, and will be introduced on premium vehicles from more manufacturers within the next few years. Both Level 1 and Level 2 systems provide driving comfort and convenience, but they require that the driver continuously monitor the driving environment for hazards and be prepared to resume control immediately when the system encounters situations it cannot handle. These are not expected to have significant impacts on the transportation system while they exist in limited numbers. As the market penetration grows, the Level 1 systems should produce some safety increase but the safety implications of Level 2 systems are uncertain because of the likelihood that drivers will misuse them by diverting their attention to other activities while the systems are in use. There is already significant evidence of this misuse in experimental findings from NHTSA's initial evaluations of the systems (Blanco et al. 2015), Google's experience when loaning its test vehicles to company employees not directly involved in the development of the vehicles, and YouTube videos[1] posted by members of the general public. This type of misuse will create new safety problems and has already cost the lives of several Tesla "autopilot" drivers.

The primary safety benefits for the foreseeable future from use of CAV technology are likely to come from Level 1 and Level 0 automation systems.

[1] See https://youtu.be/2AM9Qqcir6k and https://youtu.be/zY_zqEmKV1k.

At Level 0, the systems do not perform dynamic driving tasks on a sustained basis, but they can warn drivers about hazards or even intervene for a brief time to avoid or mitigate an imminent crash (automated emergency braking or lane departure prevention). At Levels 0 and 1, the driver must remain fully engaged in the dynamic driving task, so that the vigilance of the system and the driver support each other to produce a higher overall level of vigilance with regard to hazards. At the higher levels of automation, driver vigilance is inevitably reduced, and so the vigilance requirements on the system become significantly more severe.

Level 3 conditional automation systems will provide higher levels of driver comfort and convenience by allowing the driver to temporarily turn attention away from driving to engage in other activities, but the driver still needs to be available to retake control within a few seconds' notice when the system reaches the limits of its capabilities. It is not yet clear whether it will be possible to implement a driver–vehicle interface that can successfully manage these transitions and prevent the driver from "tuning out" so seriously that she or he is unable to intervene when needed. Although many vehicle manufacturers have steered clear of Level 3, Audi's new Traffic Jam Assist feature provides the Level 3 functionality of bringing the vehicle to a stop if the driver fails to intervene (Audi 2017; Markoff 2017).

Level 4 high automation includes a diverse collection of capabilities that need to be considered individually. These systems can replace drivers completely (not requiring driver interventions), but only under specific limited conditions, and those limitations can vary widely from system to system:

- Automated valet parking systems will park cars in parking lots or garages after the driver has exited the vehicle, making it possible to squeeze them into smaller parking spaces in areas where land is expensive. The first systems require continuous supervision by the driver using a key fob or software application on a smart phone or tablet. In the next few years, systems will be able to operate outside the driver's line of sight, in suitably equipped parking facilities that limit hazards and provide supplementary communication and sensing capabilities. Eventually, automated valet parking will be extended to any parking facility.
- Automated buses on special transitways will be developed as cost-effective alternatives to light-rail transit on high-volume urban routes (Shladover 2000). The automation technology will provide a rail-like quality of service and the ability to fit within a narrow right-of-way through accurate steering control, but at much lower cost than a rail system. The physically constrained environment of the transitway and the ability of the transit operator to equip it

with cooperative infrastructure elements should make it possible to start implementing this capability within this decade.

- Automated trucks on dedicated truck lanes are another high-value niche application of automation that should be possible within the decade by restricting access to those lanes to trucks (Shladover 2001). By excluding light-duty vehicles and vulnerable road users from coexisting with the trucks and operating within a physically constrained highway environment, the most challenging hazards can be eliminated, to enable Level 4 highway automation within the decade if the truck-lane infrastructure can be made available. There is a strong economic incentive to truck owners and operators to implement this technology because of its significant fuel-saving potential.
- Automated low-speed shuttles in campuses or pedestrian zones have been the focus of much attention in Europe through the CityMobil2 project,[2] and several small companies have been developing vehicles for this type of application. Google (now Waymo) also shifted its attention with the announcement about its "pod car" emphasis since 2014. The European work has depended on certification of the infrastructure where the vehicle travels, with special design features to limit the interactions with other road users and to ensure clear fields of regard for the vehicle sensors that need to detect hazards. Based on the reduced speeds and infrastructure restrictions, the first of these vehicles could be operational without drivers onboard before the end of the current decade (although they would still be supervised remotely from an operations center).
- Automated passenger cars on limited-access highways are likely to be the most broadly applicable Level 4 automation systems. These automation systems will probably initially (in the 2020–2025 time frame) only be usable under certain traffic conditions (such as low-speed traffic jams or high-speed operations in light traffic) or in lanes that are restricted to vehicles that are equipped for automation and/or V2V communication capabilities, analogous to the automated highway system concepts that were developed by the NAHSC in the 1990s (Rillings 1997). These restrictions will facilitate safety before the hazard detection technology has advanced sufficiently to handle all highway driving hazards, which is likely to be closer to 2030.

Level 5 full automation would enable a vehicle to drive itself anywhere and under any conditions in which a normal human driver would be able to

[2] See http://www.citymobil2.eu/en.

drive. This is the concept that captures the public imagination by allowing full "electronic chauffeur" service, including

- Electronic taxi service for people who are not able to drive (too old, too young, physically impaired),
- Shared vehicle fleet repositioning so that shared vehicle concepts can be economically efficient, and
- Driverless urban goods pickup and delivery.

These applications are the ones that could have revolutionary impacts on travel behavior and urban form by eliminating the disutility of travel time, decoupling parking locations from travelers' origins and destinations, facilitating vehicle sharing as well as ride sharing, and breaking down the boundaries between public and private transportation. However, the technological problems that need to be solved before this can become reality are extremely daunting, and so these capabilities are not likely to become available for many decades.

For each of these levels of automation, it is important to be conscious of the time between market introduction and widespread use. Even if a new feature is implemented on every newly manufactured vehicle, it will take close to 20 years for the vehicle fleet to turn over sufficiently that it will be found on the large majority of the vehicles on the road. Most technology dissemination on private vehicles is a lot slower than that because the technology is introduced only on the high-end vehicles in limited quantities before manufacturers scale up to larger-volume production, and then it depends on private individuals' voluntary vehicle purchase decisions; so it is important to allow additional decades for the technologies to propagate through the vehicle fleet.

If the government mandates inclusion of specific features on all new vehicles it can accelerate their market introduction. For example, when NHTSA mandated the inclusion of seat belts on all new vehicles, there was a gradual phase-in period so that it took 6 years for more than 90 percent of new vehicles to have seat belts, but it took 22 years for 90 percent of the vehicles on the road to be equipped with seat belts. In the absence of a government mandate, the rate of propagation depends on market forces. Past experience provides examples of the time it took from first market introduction to installation on 90 percent of new vehicles for major automotive technologies that we now take for granted as standard equipment (Jutila and Jutila 1986):

- Air conditioning, 20 years;
- Automatic transmission, 27 years;
- Power steering, 21 years; and
- Disc brakes, 10 years.

Demand-Side Impacts

The CAV technologies are likely to have diverse impacts on the demand for travel, and the net impact is likely to be challenging to estimate because of the large uncertainties on both the positive and negative expected impacts. These demand effects are expected to include

- Reductions in the need to travel, with potential for substituting telecommunications activities for travel;
- Changes in trip scheduling, with better information promoting better choices to avoid the worst congestion and safety challenges;
- More efficient selection of routes and modes based on better information about all viable alternatives;
- Reduction in disutility of travel time, encouraging realization of latent demand and potentially inducing new travel demand through locational changes;
- Increased efficiency and improved quality of service by trucking, encouraging freight modal shift toward trucking;
- Improved transit service quality, encouraging passenger mode shifts away from private personal vehicles and toward transit; and
- Electronic chauffeuring providing affordable mobility for travelers who cannot drive, encouraging them to travel more than before.

Some of these impacts are likely to reduce vehicle-miles traveled (VMT) and some are likely to increase it, which makes it particularly challenging to estimate the net VMT effect. If the mobility enhancement effects dominate, VMT is likely to increase unless ridesharing in automated jitney services becomes the preferred mode of urban and suburban transport (in which case VMT could decrease).

Supply-Side Impacts

The CAV technologies are likely to have even larger supply-side effects, producing significant changes in multiple aspects of traffic operations. These changes are likely to affect virtually all of the significant measures of effectiveness by which traffic operations are measured, including safety, travel times, congestion, energy use, emissions, and travel comfort and convenience. In most cases, these effects will depend heavily on whether the CV and AV technologies are implemented individually or in combination. These effects are expected to include

- Changes in traffic flow stability based on differences in vehicle following dynamics,

- Changes in highway lane capacity based on differences in vehicle following gaps,
- Increases in highway bottleneck throughput based on more responsive traffic management and ability to implement situation-dependent speed control,
- Reduction in traffic disturbances from lane drops and entrance and exit ramp flows through coordinated vehicle merging,
- Improved ability to manage incidents based on higher-fidelity information for incident responders and for travelers, and
- Improved multimodal corridor management in urban corridors through enhanced information and control mechanisms.

Mode-Specific Impacts

The later sections of this appendix address the freight and passenger movement impacts separately because there are some significant differences between them on both the supply and demand sides. These distinctions can be lost if they are aggregated at too gross a level.

CENTRAL IMPORTANCE OF UNCERTAINTY IN CONSIDERING FUTURE TECHNOLOGY IMPACTS

Forecasting the development of information technology is fraught with uncertainty, since this is a domain in which the "disrupters" of today become the "establishment" of tomorrow and the cycles of technological upheaval occur frequently. Silicon Valley thrives on revolutionary change and destructive innovation, with the expectation that the life cycle of each technological revolution is likely to be only a few years, up to maybe a couple of decades for the most durable ones. The contrast with planning for transportation infrastructure, with its expected functional lifetimes of many decades, is stark.

When we enter the realm of CAVs, we are dealing with a complicated mix of information technology, vehicle technology, and infrastructure technology. These three domains are radically different in their product life cycles and investment horizons. Although information technology is on the fast track, with product functional lifetimes measured in months, vehicles are designed for functional lifetimes of years and civil infrastructure must be designed to last for decades. These differences are to a large extent inherent in the capital intensity of the products and production processes associated with each industry, so we should not expect vehicles and civil infrastructure to change as rapidly as mobile phones and their application software.

The most important principle to take away from this observation is that decisions about the future of our transportation infrastructure need to be robust with respect to technological uncertainty, rather than being highly tuned to specific predictions about technological outcomes. Each technology forecast should be viewed as a fuzzy estimate, with a wide range of possible outcomes that could range from much faster and higher capabilities to much slower and lower capabilities than the nominal prediction. Regardless of where reality eventually falls within this range of possible outcomes, transportation decision makers need to make sure that they have not locked themselves into an untenable situation by becoming too heavily dependent on one specific outcome, requiring a specific technological capability to become available for use by a specific future date in order to justify the viability of an infrastructure investment or to meet a mobility need.

The more optimistic predictions of change in information technology also need to be tempered by the realization that the vehicle and infrastructure technologies *cannot* change as rapidly, and so these are likely to become the pacing items for the rate of change in the road transportation system of the future.

Although CV and AV have been grouped together for consideration here, their situations are quite different in terms of technological maturity and uncertainty. The CV technology has been under development for almost two decades, with close coordination among the government and the vehicle and communications industries. Assuming that NHTSA's (2017) Notice of Proposed Rulemaking to create FMVSS 150 evolves into an enforceable standard, all new vehicles will be equipped with a specific CV capability that can support a variety of transportation information and automation functions starting in the early 2020s. The profile of market penetration growth should then be reasonably predictable based on the rate of introduction of new vehicles and the retirement of old vehicles, although this could be accelerated if interest grows in the availability of after-market retrofit V2V communication systems. Deployment of the cooperative I2V/V2I roadside infrastructure is less certain, since this will depend on decisions to be made by state, regional, and local government agencies that have not yet been convinced of the benefits they will derive from this. Fortunately, many of the benefits of CV technology for highway operations can be gained from use of the V2V data, without depending on the uncertain infrastructure investments.

The uncertainties are much more significant for the AV technologies, which are not as mature for the higher levels of automation (SAE L3–L5). Those higher levels of automation are the ones that are likely to have the more profound implications for the future Interstates. The uncertainties cover several dimensions:

1. How capable will the automation technology be of performing the complete dynamic driving task within various operational design domains, and when will those capabilities first become available for use by the general public?
2. After each technology becomes available commercially, what will be the consumer interest and willingness to use it (either by purchasing it in their personal vehicles or using it through a shared mobility service)? How quickly will that interest grow, and how will that be modulated by the cost of the technology? Will that interest cool significantly after fatal crashes (killing innocent bystanders) caused by the automation technology are reported?
3. How much interest will there be in the United States in development of new greenfield (or brownfield) technology-focused cities that could be designed from the start to have transportation infrastructure well suited to AV operations? If there is significant development along these lines, the AV technology could be used earlier and more widely than if it needs to wait until it is capable of handling the full complexity of traffic conditions on roads that must be shared with all other road users.

None of these questions can be answered with any certainty today, which means that the prospects for widespread use of vehicles capable of higher levels of automation in the coming decades remain subject to a high degree of uncertainty. We could be looking at a future 50 years from now in which only specialized niche application vehicles are highly automated, or one in which a substantial fraction of all road vehicles are driven most of the time by automation systems. However, we can be certain that we will *not* be in a situation in which all road vehicles will be driven automatically—even apart from the technological challenges, there is still a matter of consumer acceptance. Adoption of automation technology will be a voluntary consumer decision, and since there is a segment of the population that is actively hostile to automated driving, there will continue to be a market for new vehicles that are not highly automated.

REGIONAL DIVERSITY OF IMPACTS

Although the market for road vehicles is a national one, meaning that the same vehicles are available for use by travelers throughout the country, the roadway infrastructure is likely to be even more diverse across the country (across regions and between urban and rural land uses) than it is today. The future operations of the highway network will be more dependent on the cooperation between in-vehicle and infrastructure systems than they are now, given the growing importance of I2V and V2I CV systems to enable the vehicles and the roadway infrastructure to function as a well-integrated system. This means that it will be increasingly difficult to treat the National Highway System as a single consistent system unless extraordinary efforts are invested to promote nationwide consistency and uniformity.

The forces working against national consistency are several and powerful:

1. Differing affinities of the populace for reliance on new vehicle technology and different levels of resources available to be early adopters (both supply- and demand-side effects). These differences are not only regional (sun belt versus rust belt or coastal versus inland) but also tied to the urban versus rural divide.
2. Different financial and human resources available to public agencies in different parts of the country to develop and operate I2V and V2I cooperative systems. These could represent differences between high-tax and low-tax states, prosperous versus depressed metropolitan regions, urban versus rural counties, or "self-help" jurisdictions (those that choose to tax themselves specifically for financing transportation improvements) versus those that are dependent on the largesse of their state or federal agencies.
3. These trends will be amplified by the growing digital divide within the population, which already tends to be correlated with these regional differences.

The likely differences in regional economic growth (high-tech regions growing, rust-belt regions shrinking in population and economic activity) are only going to exacerbate these forces at the national level. The one significant advantage that the less prosperous locations have is better availability and lower cost for new right-of-way that could be used for new transportation facilities or expansions of existing facilities. The development of new highway facilities that are designed specifically for use by more highly automated vehicles could be a major factor in leveling the field nationally in favor of the less prosperous or advanced locations that want to enjoy the transportation benefits from higher levels of road vehicle automation.

PASSENGER TRAVEL DEMAND IMPLICATIONS OF CAV TECHNOLOGY

The CAV technologies will have impacts on both the supply and demand sides of transportation, and those impacts will differ for passenger and freight movement. In this section and the subsequent sections, these respective impacts are discussed in largely qualitative terms, since detailed quantitative estimates would be speculative at this early stage.

The passenger travel demand implications of CAV technology are discussed first, followed in subsequent sections by the freight travel demand and the combined supply-side implications. Note that the CAV technologies are likely to have diverse impacts on travel demand, with some tendencies toward increasing VMT and others toward decreasing VMT. With large uncertainties attached to both positive and negative tendencies, it becomes particularly challenging to predict the likely net impacts. The U.S. Department of Energy recently published a study to predict the net impacts on energy consumption based on two dimensions of future urban travel—the level of automation and private personal versus shared vehicle usage (DOE 2017), and identified dramatically different impacts depending on which level of automation and which level of ridesharing become dominant.

CAV and Related Technologies Reducing the Number of Vehicle Trips

Telecommuting to Work at Home

This is already a powerful trend, and it is not likely to weaken in the coming decades, but is only likely to strengthen. With the growth in employment in information technology and related fields that depend on individual creative work on computers, this can be a very efficient way of accomplishing the work that is attractive to both employers and employees. It saves on costs of office space for employers and saves on commute time and expenses for employees, but it can make it more challenging for employers to assess work performance of their employees. It is also consistent with the growth of the "gig economy," with people working as independent contractors rather than as regular employees, and often working fractions of weeks on an as-needed basis. Over the long term, this could lead to significant reductions in the traditional peak-period commute traffic volumes on urban and suburban Interstate highways.

Remote Work Centers, Closer to Homes

This is an intermediate step between traditional office work patterns and telecommuting, allowing employees to do their work at shared worksites scattered throughout a region rather than at a central site. This may not reduce the number of trips as much as it reduces the length of the work trips that are taken to the remote work centers, but its impact on traffic volumes and patterns could still be substantial for urban and suburban Interstate highways in locations that are based on a knowledge economy.

Teleconferencing and Virtual Reality Reducing Longer-Distance Trips to Meetings

Teleconferencing is already having an influence on reducing long-distance business travel based on the potential to save significant time and money, but it is still a relatively narrow application because it is not yet a very convincing substitute for face-to-face contact for many purposes. There is a potential for great growth here, particularly as virtual reality or augmented reality can provide an impression of more direct personal contact among people who do not already know each other. This could become the preferred mechanism for routine sales calls or for a variety of other meetings that currently require travel, which could in turn significantly reduce the number of business trips that are currently taken, with significant implications for personal business travel demand on all categories of Interstate highways.

Online Retail Reducing Shopping Trips

Online retail is already having dramatic impacts on traditional brick-and-mortar retail, and that trend is likely to grow. The suburban shopping malls of the 1960s and 1970s are suffering serious decline, which is likely to accelerate, leading to significant changes in patterns of shopping travel. Transportation infrastructure that was built to serve those malls is likely to be underutilized unless the mall owners are able to redevelop their properties into destinations that are attractive for other purposes. This is an example of a technology-driven trend whose longer-term implications are difficult to discern, beyond the general observation that it is having a significant impact on shopping trip–making behavior, with likely implications for urban and suburban Interstate highway usage.

Rideshare Matching and Transportation Network Companies Facilitating Ridesharing, Increasing Vehicle Occupancy

This is perhaps the most widely discussed recent trend in transportation, particularly in its coupling with vehicle automation. There has been much overheated speculation about the end of private vehicle ownership, a potentially dramatic decline in the market for new motor vehicles, and the end of the need for parking spaces for vehicles that will be in continuous use. This speculation has been fueled by the entry of Uber, Google (Waymo), and many major vehicle manufacturers into the shared-use ride-sourcing market based on anticipated replacement of human drivers by automated driving systems. That type of future scenario would only be viable if Level 5 automation (or Level 4 automation with very few ODD limitations) became technologically feasible and affordable—a prospect that is likely to come in the very distant future, if ever (for reasons to be explained in the section on effects at different planning horizons). The reductions in vehicle trips would only occur if large portions of the population were to become comfortable with sharing their *rides* (not just vehicles) with total strangers. There is little current evidence to indicate that this would be acceptable to the broader population when considering factors such as personal privacy, personal safety (especially for women or children traveling alone, and in the absence of an authority figure in the vehicle), and widely differing personal preferences regarding choices of entertainment and personal hygiene and behavior. There has also been some recent evidence from cities in which Uber and Lyft are serving large numbers of travelers to indicate that they are drawing more people away from conventional public transit than from private personal vehicles, leading to lower overall vehicle occupancy and worsened traffic congestion (Schaller Consulting 2017).

Technology Changing the Character of Trips

Apart from the trip reduction potential discussed in the section on CAV and related technologies reducing the number of vehicle trips, there is a potential for information technology to change the character of the trips that are taken even if the number of trips does not decline. There several ways in which future trip-making choices could change from the current norms.

Improved Real-Time Traffic Condition and Route Guidance Information Leading to More Efficient Routing

Travelers have been receiving real-time traffic condition information from mobile phone applications in recent years, helping them to avoid some of the worst traffic congestion problems. However, the information is still frequently inaccurate or obsolete, which limits its usefulness for decision making by travelers. In the coming years, the quality of this information should improve significantly, making it more attractive to a larger share of the traveling population. That should help reduce the current inefficiency in traveler responses to incidents, enabling them to find faster and less congested alternatives to the routes that have been affected by incidents. Although this will be good for travelers and traffic managers, it is not clear that it should have much impact on the design or construction of future Interstate highways, apart from the need to include provisions for the information infrastructure to support collection and dissemination of improved traffic condition data.

Parking Information Reducing Wasted Travel Seeking Parking

A significant proportion of urban driving is currently wasted mileage by drivers seeking parking spaces (Shoup 2007). Improved parking information collection and dissemination should help reduce that wasted mileage and the associated impacts on urban traffic congestion, pollution, and energy consumption. However, it is unlikely to have much impact on the Interstate highways of the future.

Reduced Importance of Traditional Shopping Malls and Office Parks as High-Volume Destinations

Patterns of urban land use and activity are likely to change in the coming decades as a consequence of some of the changes in work patterns and increased reliance on the Internet. The impacts on shopping malls were already discussed, but office parks are also potentially subject to decline if more people telecommute. This means that some of the current edge-city activity centers could decline in importance, especially if they lack other reasons for being. Highway infrastructure that was built to serve these sites could become obsolescent as activity patterns change unless the owners of these sites are agile in finding or creating other uses for them.

If Traditional Commute Work Trip Patterns Decline by Enough, Special-Event Travel Could Become the Defining Case to Determine Capacity Needs

The current urban and suburban Interstate highway network has in large part been scaled to serve the morning and evening commuter peak travel demand, which is the heaviest travel demand experienced in most locations in the United States. If the changes in information technology cause work trip patterns to change significantly, the peak travel demands could be defined differently, based on considerations such as sporting events, festivals, holiday periods (skiing weekends), or emergency evacuations in locations that are vulnerable to weather emergencies. This could put pressure on planners to rethink how they determine the capacity needs for their Interstate highway networks, which may find themselves overbuilt in some locations but needing expansion in others.

Technology Increasing the Number and Length of Vehicle Trips

Just as information technology has the potential to reduce travel demand, it also has the potential to increase demand in other ways. With the large uncertainties on estimates of both increases and decreases in travel demand, it becomes particularly challenging to estimate what the net changes in demand are likely to be.

Empty Backhaul Trips for Repositioning Shared-Use Vehicles to Make Their Next Trip

The concept of shared-use vehicles (car sharing) currently depends on the vehicles being returned to a fixed location where they can be accessed by the next user or (in the future) on a highly automated driving system taking the vehicle directly to its next user's origin. The attraction of the latter concept is increased convenience for the users and higher utilization of the vehicles, but it involves empty backhaul mileage for the trip between the first user's destination and the second user's origin. Several case studies have included estimates of the amount of extra travel that would be required, which depends heavily on the local travel patterns and the size of the shared-use fleet. For example, Viegas and Martinez (2017) showed that when they simulated the use of 8- and 16-passenger shared taxi services to provide the feeder service to rail transit and all other passenger trips in the Lisbon urban region, those vehicles would be operating 20 percent of the time with no passengers onboard while they deadhead from one passenger-carrying trip to the next.

In a related study for Lisbon, Viegas and Martinez (2015) showed that the overall weekly VMT would increase by 6 percent from today's baseline if their shared taxis were deployed in combination with high-capacity metro service or by 22 percent if all trips were to be served by the shared taxis in the absence of high-volume public transit service. Fagnant and colleagues (2015) simulated shared automated vehicle services for a 12 × 24-mile region in Austin, Texas, and found that empty backhaul travel added 8 percent to the VMT for the area, with an average wait time of 1 minute. These studies have been for relatively short-distance urban driving applications, but it is not clear how viable the shared-use concept will be for the longer trips that would be more likely to use urban and suburban Interstate highways.

High Automation of Driving Allowing "Drivers" to Make Productive Use of Travel Time

One of the major potential benefits to users of highly automated vehicles is the notion of the electronic chauffeur that could take over most or all of the driving under some road and traffic conditions so that the user could use the traveling time to do other things (work, play, or sleep). This severely reduces the effective cost of that travel time to the user, which could encourage people to take more and longer trips, including choosing to live farther from their workplaces. This triggers one of the major potential concerns about highly automated driving—that it will release significant latent demand and may induce new travel demand by encouraging urban sprawl. This should be a major consideration for the long-term planning of future Interstate highway developments, which may need to accommodate such demand unless policies are implemented to actively discourage it.

High Automation of Driving Enabling More Travel by People Who Currently Cannot Drive or Are Intimidated by Highway Driving

Highly automated driving systems offer the prospect of restored mobility to senior citizens who are no longer able to drive themselves, as well as relieving parents of the burden of chauffeuring their children everywhere they need (or want) to go. These potential increases in mobility of the nondriving population also raise the prospect of releasing latent demand and thereby increasing the overall volume of travel, since trips that are currently too costly or inconvenient could become significantly less costly or inconvenient. This could lead to a growth of up to 14 percent in VMT, as projected in recent research that assumes nondrivers would travel as much as their driving counterparts in the same age and gender categories (Harper et al. 2016). The implications may be more significant for short-distance trips on local streets than for long-distance Interstate highway trips.

High Automation Advances to the Level of Enabling Automated Taxi Services on Freeways Could Lead to Increased Demand for Urban Freeway Traffic

Most of the current consideration of automated taxi-like services by major automotive companies and technology companies such as Google/Waymo and Uber has been focused on low-speed, short-range, urban applications. However, when the automation technology improves to the level that it can be entrusted with freeway driving, there could be an impact on urban and suburban Interstate highway traffic, based on the addition of empty backhaul driving to reach the next traveler. If the taxi service is also based on shared occupancy of the vehicles, the higher occupancy could compensate by eliminating some vehicle trips.

High Automation of Driving Could Encourage Remote Parking of Personal Vehicles on Low-Cost Land in Peripheral Locations

One of the long-term visions of the highest levels of automated driving has been eliminating parking from high-density urban cores and relying on the automated driving system to drive the empty vehicle back and forth between the user's destination in the urban core and a remote parking facility on cheaper land in the outskirts. This would create extra empty mileage for the round trips between the travel destination in high-cost locations and the remote parking sites, which is likely to have significant adverse implications for traffic volume, energy, and the environment. The long-term implications need to be considered seriously for urban and suburban Interstate highways that would provide access to the remote parking sites, but this is unlikely to become technologically feasible for several more decades (and it will take further decades for the population of suitably equipped vehicles to become dominant).

If the Cost of Travel Declines Dramatically, Consider Growth of New Types of Zero-Occupancy Trips for Nontravel Purposes

We normally think about the demand for travel being a derived demand, based on the need to move people or freight from one location to another. However, vehicles could be driven to serve other purposes if their cost of operation were low enough. This is where the concept of the mobile billboard could come into play, a vehicle that is just driven throughout the roadway network so that it can be seen by the people in other vehicles or along the roadside. It would represent a new form of demand for VMT with zero occupancy, which raises broader policy questions about whether it should be condoned. It has the potential to add to the demand on major Interstate freeways that have high enough traffic volumes to be interesting to advertisers.

FREIGHT TRAVEL DEMAND IMPLICATIONS OF CAV AND RELATED TECHNOLOGIES

The implications of changes in the demand for goods movement are likely to be at least as significant for the future of the Interstate Highway System as the changes in movement of people. The dominant factors in goods movement demand are much larger economic forces, such as the levels of international trade with different trading partners (especially Canada and Mexico), the type of goods involved in that trade, and the overall health of the different sectors of the U.S. economy and of its regions. The highway system is only directly affected by the demand for goods movement by truck, but that is in turn affected by trucking's service and price competitiveness with other modes for the goods that could potentially be moved by multiple modes. This is where the influence of CAV enters the mix, because it can improve both service and price competitiveness of trucking.

The CAV influence on service improvements includes

- Better real-time traffic and weather information enables truck operators to choose better routes and dynamically change routes to avoid delays, reducing delays and improving delivery time reliability.
- Operation of trucks using cooperative ACC and platooning increases the capacity and smooths traffic on congested truck corridors, reducing delays and improving reliability of delivery times.
- Use of Level 3 and Level 4 automation to take over tedious driving tasks makes truck driving a more attractive occupation, helping to relieve the current shortage of truck drivers.
- Level 3 and Level 4 automation eventually enables modification of driver hours-of-service rules so that drivers can work longer shifts without fatigue and trucks can complete longer-haul delivery runs sooner, increasing their competitiveness with air for higher-value shipments.
- When Level 4 automation matures to the point that a truck could drive the entire length of an Interstate highway trip without a driver onboard, the trucks could be driven continuously without regard to hours-of-service limitations, limited only by the distance between necessary refueling stops.

These service improvements can also help reduce truck operating costs, making it possible for trucking to become more price competitive with rail, and perhaps increasing the length of haul at which trucking is seen as the best modal alternative. Additional opportunities for CAV to improve the price competitiveness of trucking include:

- CACC and platooning enable trucks to drive closer together, saving 10 percent to 15 percent of their fuel consumption costs through reduced aerodynamic drag.
- Efficiency and traffic flow improvements already cited above in the service category provide further fuel consumption reductions, saving additional operating costs.
- In the longer term, when CAV technology enables the following trucks in a platoon to be driven without a driver onboard, the driver labor costs could be eliminated, leading to a significant operating cost saving. However, this concept has further implications for the highway infrastructure because it would probably require the development of staging areas at major freeway entry and exit points (analogous to railroad marshaling yards) where the platoons would be assembled and disassembled and where control would be

transferred between drivers (who would still drive the local pickup and delivery portions of the trips) and the automation system.

- In the even longer term, when CAV technology enables any truck on an Interstate highway to drive without a driver, the labor costs for truck operations could be further reduced.

The implications of these potentially significant changes in use of trucks on Interstate highways will not be uniform across the Interstate network, but are likely to differ between long-haul operations on rural highways and short-haul operations on urban highways (which are more likely to be dominated by port drayage and pickup and delivery operations). The long-haul operations will be more influenced by the drag reduction and driver labor-saving opportunities, whereas the short-haul operations will be most affected by the congestion reduction opportunities. The timing for realizing these benefits is also likely to be influenced by the availability of resources for development of dedicated truck lanes where the trucks can take maximum advantage of these opportunities to improve their operations (especially for the higher levels of automation). Future Interstate highway planning should take serious account of how to design, operate, and finance such dedicated trucking facilities within the Interstate right-of-way.

Other advances in information technology not directly classifiable as CAV are also going to have important effects on the demand for goods movement on the future Interstate Highway System. Further growth of online shopping will continue to change consumer product distribution patterns, with more focus on direct home delivery rather than delivery to retail stores. This could affect decisions about locations of warehouses and both geographical and temporal distributions of deliveries, especially on urban and suburban freeways. Furthermore, the growth of local three-dimensional (3-D) printing for manufacturing could shift freight demand away from fabricated products and more toward the bulk raw materials used by the 3-D printers. It is not clear yet whether that may favor rail shipment of the bulk materials over truck shipment of the fabricated products.

SUPPLY-SIDE IMPLICATIONS OF CAV TECHNOLOGIES FOR THE INTERSTATE HIGHWAY SYSTEM

The most direct impacts of the CAV technologies on the future Interstate Highway System will be on the supply side rather than on the demand side. These technologies will produce significant changes in the characteristics of vehicle traffic, with important implications for safety and efficiency of vehicle movements. The consequences for design and operation of the highway system are not yet entirely clear, but will need careful study. The diversity of changes is at least as broad as the diversity of CAV alternatives that are likely to be implemented.

Collision Warning and Avoidance Systems

These systems could potentially reduce current crash rates by about half. Since crashes have been estimated to cause about 28 percent of the congestion on urban freeways (Varaiya 2005), this could potentially reduce nonrecurrent highway congestion by about half that amount, leading to reduced delays and improvements in travel time reliability.

Improved Traffic Management and Incident and Weather Management

These applications, which are enabled by CV technology, could further reduce congestion impacts of incidents and weather and facilitate emergency evacuations of low-lying coastal areas threatened by sea level rise and extreme weather events.

Traffic Management Strategies Using Variable Speed Limits (VSLs) and Coordinated Ramp Metering (CRM)

These strategies can be implemented based on V2I collection of traffic probe information, with recommendations provided to drivers using roadside variable message signs, or they could depend on I2V information to provide in-vehicle displays to drivers or direct access to control the maximum set speeds of ACC systems. As the level of information and control increases, they should have increased impacts on improving the effective capacity of freeway bottlenecks, partially relieving some choke points, and improving incident response (Lu et al. 2015).

Integrated Corridor Management (ICM)

Increased use of CV technology to collect and disseminate real-time traffic information can help managers of freeway, arterial, and transit networks to integrate their operations to provide more effective utilization of the capacity available in urban and suburban corridors, especially when responding to incidents that disrupt some of these networks. This will reduce delays and improve trip time reliability for a wide range of travelers and vehicles.

Advance Reservations for Highway Trips

CV technology offers the potential for travelers (private personal travelers or truck drivers) to request advance reservations for trips on congested highways, guaranteeing them preferential access at their reserved times. This could help significantly in spreading the peak congestion periods, encouraging travelers who do not reserve as early or not at all to travel at times away from the peak. This could of course also be coupled with congestion charging via CV technology, adjusting the prices for travel based on time of day or current conditions, further encouraging peak spreading.

Extended Electronic Toll and Traffic Management

Electronic toll collection technology is already in widespread use and is displacing traditional cash-based toll collection for a variety of reasons. This trend should accelerate, and the technology should enable, more advanced applications of dynamic electronic road pricing based on real-time traffic condition information. This enables both traffic managers and travelers to make real-time decisions based on the most up-to-date information about current traffic conditions and problems.

Right-Sized Public Shared-Use Automated Transit Vehicles

The future generations of public transit service are unlikely to look like today's 40-foot buses, which have not been very successful at attracting riders in all but a handful of cities. In the future, when Level 4 automation technology makes it possible for a bus to operate without a driver on its own urban busways or on bus lanes on the Interstate System, a more flexible type of transit service will be possible, with vehicles sized to the anticipated volume of traffic demand because the driver labor cost is no longer the driving factor. Applying CACC or platooning technology to the transit vehicles in the bus lane can help to provide higher passenger throughput in locations where that is a potential concern. Such bus lanes could become important elements of the future urban Interstate highway network.

Automated Truck Platoons

This is one of the initial CAV operational improvements that could be achieved within the next 5 years, based on technology that is already in advanced prototype testing (Dutch Ministry of Infrastructure and the Environment 2016; Tsugawa et al. 2016). It can provide significant lane capacity and traffic flow stability improvements while also saving operating costs for fleet operators, potentially inducing more truck demand. The impacts on operations depend strongly on market penetration, and so it will take some time for the percentage of equipped trucks to grow to the level that will have a significant impact on Interstate corridors with high volumes of truck traffic.

The more advanced version of this technology, which could gain larger operating cost savings by operating the following trucks without drivers, would be able to enter the market for public use more quickly if dedicated truck lanes or corridors were available on key Interstates to segregate the trucks from the hazards posed by recklessly driven cars and motorcycles. This is an alternative that should be explored on the infrastructure side now so that it could be implementable in 10 years, when the driverless platoon follower technology could become feasible for use within such a restricted ODD.

Automated Urban Freight Distribution

CAV technology will produce a variety of innovations in urban freight distribution, especially with the potential for smaller and more specialized delivery vehicles that could operate without drivers under certain ODD restrictions in future decades. These will probably have more of an impact on local urban traffic than on Interstate highway operations, although there could be some impacts on urban Interstate highways near goods distribution hubs.

Cooperative Adaptive Cruise Control and Automated Merge Coordination

These systems combine CV and AV technology to increase the effective density of highway traffic without producing traffic instabilities, thereby significantly increasing throughput at high market penetration (up to a factor of 2) (Shladover et al. 2012). In this way, the existing physical infrastructure of an Interstate freeway could potentially accommodate twice as many vehicles per hour as it does today, without reductions in speed or flow breakdowns (no stop-and-go disturbances). This can be accomplished with Level 1 automation (speed control only) and V2V communication, and so it does not depend on dramatic technological advances, but only on increased market penetration of vehicles with the needed capabilities.

Level 4 Automation on Freeways

This level of automated driving within the ODD of limited-access freeways could support dramatic improvements in capacity and congestion reduction, especially if lane(s) could be dedicated for their use (maybe up to a factor of 3 in capacity per lane compared to no automation) (Michael et al. 1998; National Automated Highway Systems Consortium 1997). This is a situation in which the combination of the in-vehicle automation technology and the dedicated physical infrastructure can produce significantly more benefit than either one or the other in isolation.

These substantial capacity increases on freeways could be the safety valve that reduces the need for much additional civil infrastructure, but better integration with local arterial traffic operations will be necessary as part of the implementation to avoid simply shifting the bottlenecks to the arterials and freeway entrances and exits. The benefits to the freeway network operations should be sufficiently large to justify the relatively modest investments that are likely to be required for the improved arterial coordination.

The cost of providing connectivity and system management capabilities on the roadway infrastructure should be a minuscule fraction of the costs of the civil infrastructure construction and right-of-way, but the operational and maintenance costs will be a more significant fraction of the deployment costs, so they need to be factored into the financing model explicitly. Maintenance cost considerations will have to include better visibility of pavement markings and signage to help computer vision systems on vehicles, and also management of pavement wear if vehicles all follow the same paths very accurately (this can be resolved by deliberately introducing random misalignments into the vehicle steering guidance algorithms). The current Interstate financial support model will need to be reconsidered, since it is based on the more traditional highway technologies, in which the large majority of the life-cycle cost of the system is in the original capital construction costs. It will be important to avoid creating disincentives for states to invest in the most cost-effective highway alternatives because the funding formula favors support for capital costs over operating and maintenance costs.

Cybersecurity introduces a new set of issues for highway designers and operators to consider. There is a significant risk of transportation system disruption if vehicles are hacked, and there is a need for (probably standardized approaches to) protection of the traffic management systems' information infrastructure (which in turn affects infrastructure operations and maintenance costs and staffing).

EFFECTS AT DIFFERENT PLANNING HORIZONS

The previous sections of this appendix have discussed the types of impacts that information technology is likely to have on the future Interstate Highway System in general terms, which is the easier part of this look ahead. The harder part is discerning how long it is likely to take for the different impacts to occur, based on the uncertainties about the pace of technology advance and the rate of user acceptance of the technology after it has been developed. Further uncertainties arise based on future changes in economic activity, both national and international, and in the demographics of the U.S. population.

The effects under consideration here are related to the overall study goals of serving network traffic flows more efficiently and exploiting innovation and advances in technologies to improve system safety, resilience, management, and operations. This is a broad set of potential impacts, which can at best be discussed in semiquantitative terms, rather than getting into highly refined numerical exercises. Following the guidance of the committee, the impacts are considered based on planning horizons of 10, 20, and 50 years, with increasing levels of uncertainty as the horizon recedes.

10-Year Horizon

The 10-year horizon forecast is dominated by the inertia in the current transportation system, which cannot change rapidly on either the vehicle or infrastructure side. Many of today's unequipped vehicles will still be on the road at that time, and the vehicles with more advanced capabilities will still be a small fraction of the new vehicles purchased each year, so they are likely to remain a small fraction of the overall vehicle population. Information technology modifications will be progressing gradually on the infrastructure side if funding is available to pay for them, but physical modifications to the roadway infrastructure are not likely to have progressed far, given the length of the lead times involved for the full environmental review and construction processes.

- Expect significant connectivity across the vehicle fleet, with favorable impacts on safety and traveler information and trip planning, based on the assumption that the NHTSA mandate to deploy V2V communication systems for safety proceeds as planned. If that mandate is dropped or the DSRC spectrum is lost, this important enabler of many enhanced functions will at best be delayed significantly.
- Highway operators should be deploying infrastructure for I2V and V2I connectivity and transportation network management to support the most efficient operations. This will probably be primarily in the states and regions that are most advanced and have the most resources, but it is not likely to be evenly distributed around the country. The extent of these deployments will depend heavily on the policy and funding decisions that are taken by the federal government during the coming decade.
- Limited applications of partial freeway automation will be in place based on sales of Level 1 and Level 2 systems to consumers. The Level 1 ACC systems could be quite widespread, but it is not clear how many of them will be combined with the V2V communication systems to produce the enhanced CACC capabilities. The Level 2 automation systems will probably still be at low market penetrations, not yet having significant impacts on traffic conditions, since customers do not receive that large a benefit for the additional cost.

The net effects on freeway operations will probably be too small to measure throughout most of the country.

- Truck CACC and platooning systems will be used by some major truck fleets on major freight corridors and will be exposing the public to the experience of sharing the road with partial automation systems. They will probably not be in wide enough use to have a significant impact on traffic conditions.

In summary, the changes from today will be relatively modest, and there is a low uncertainty on that prediction because of the large inertia in both the vehicle and infrastructure systems that impedes rapid changes.

20-Year Horizon

The 20-year forecast has a much larger uncertainty than the 10-year forecast, especially with regard to the vehicle automation technology and its impacts. However, it appears highly likely that vehicle connectivity of one type or another should be virtually ubiquitous by then, providing comprehensive information to travelers and transportation system operators to assist them to make better decisions. The fate of V2V connectivity for collision warning and cooperative automation is not as certain, since this depends to a considerable extent on whether the NHTSA rulemaking requiring DSRC broadcasts by all new vehicles is actually implemented. Even if this rulemaking does not go forward, there is a reasonable chance that other wireless technologies, based on 5G cellular, could serve a similar purpose, but with some delay in implementation.

With regard to the vehicle automation technologies, the topics that are most important for the future operations of the Interstate Highway System are:

- Truck platooning should be commonly available, saving energy and emissions and improving traffic flow, and its economic benefits in terms of labor cost savings could be greatly increased if dedicated truck lanes are developed in major Interstate freight corridors.
- CACC and platooning of passenger cars and transit vehicles could produce significant operational improvements for urban Interstates (reducing congestion, energy use, and emissions), especially if dedicated lanes are provided for their use.
- Level 4 cooperative automation of vehicles for operation on well-protected dedicated lanes within Interstate highways should be feasible, and building such lanes will provide a significant stimulus to the development and use of these vehicles. These dedicated lanes for cooperative highly automated vehicles could offer substantially

higher capacity, safety, and possibly speed than normal highway driving, producing substantial impacts in the locations where they are implemented. If dedicated lanes are not provided, the Level 4 automation system capabilities and impacts will be much more limited and it will take significantly longer for them to come to market because of the technical challenges of ensuring their safety in mixed traffic.

There is a moderately high level of uncertainty about how rapidly these changes will occur and how large their net impacts will be.

50-Year Horizon

The 50-year forecast is fraught with extremely large uncertainties because of the large variety of influencing factors that could change in dramatic ways. The overall economy and society could change in ways that we cannot imagine today, and technologies that we cannot envision today could become reality. The 50-year time frame could be adequate to resolve the daunting technological challenges to Level 5 automation of road vehicles, and it could also produce other technological changes that might dramatically reduce the need for road travel (virtual reality encounters substituting for live entertainment and/or business meetings, telecommuting dominating work environments in many occupations, alternative modes of travel such as the Hyperloop becoming highly competitive, and so forth).

Absent these kinds of revolutionary developments, the influences of CAV technologies on the Interstate Highway System in 50 years are likely to include the following:

- High levels of (cooperative) automation are likely to be in widespread use for all classes of vehicles on the Interstate highway network, providing significant operational and safety improvements. When the market penetration of the more highly automated vehicles reaches a suitable threshold, it becomes politically easier to segregate these vehicles from the manually driven vehicles, leading to large increases in throughput for the lanes with the highly automated vehicles. The energy consumption and emissions from these vehicles should be reduced from current levels based on smoother speed profiles and reduced aerodynamic drag from shorter following distances. However, if the infrastructure investments for segregated roadway infrastructure are not made, the throughput and efficiency gains will be reduced significantly.
- Regardless of the rate of progress with highly automated vehicle technology, the vehicles driving on the Interstate highways will

continue to include some conventional manually driven vehicles and vehicles with lower levels of driving automation capabilities. These will be used by people who cannot afford the newest vehicles, people who prefer to drive their legacy vehicles, and people who are opposed to highly automated driving for various personal reasons. The percentages of these vehicles are likely to vary widely among urban regions and between urban and rural highways even after highly automated freeway driving is generally available on new vehicles (just as the percentages of vehicles with sunroofs or ACC vary widely today).

- Widespread use of automation could be influencing locational decisions and travel patterns, with potential for both positive and negative societal impacts. If the low cost and ease and convenience of automated road travel releases latent travel demand, this could lead to significant increases in the volume of road traffic. Over the long term, if this leads to changes in land use patterns and induces people to travel longer distances to satisfy their regular needs, it could also induce new and longer trips, producing even larger increases in the volume of road traffic. Policy makers will need to confront these challenges to determine what compensatory measures may be needed to discourage excessive growth in travel, with its concomitant energy and environmental costs.

Concluding Note on Technological Challenges

These projections are more conservative than most published and widely cited predictions, based on concerns about several severe technological challenges that need to be overcome before it will be possible for software to drive road vehicles at least as safely as human drivers can. This means that the road transportation system will continue to be populated by a mixture of vehicles with widely varying levels of automation for the foreseeable future. Manually driven vehicles will continue to be part of the mix, along with vehicles using the lower levels of automation to enhance the traveling experience, even after more highly automated vehicles become available for public use.

Automation systems at Level 3 and above produce fundamental changes in the driving process, which create even larger challenges for technology than they do for regulations. For the first time, technological elements are taking the primary responsibility for ensuring the safety of the vehicle occupants and other road users away from the human driver. At Level 3, this responsibility is taken temporarily and may be returned to the human driver on short notice (several seconds), but at Level 4 it is taken over for a sustained period (as long as the vehicle remains within its specified ODD), and at Level 5 it may be taken completely. Although no explicit safety standards have been specified yet, it is not unreasonable to expect the automated driving system to maintain at least the level of safety of average human drivers today (some observers contend that it is more likely to require 10 times the safety of average human drivers in order to be socially acceptable). As explained in Shladover (2014), for road travel in the United States today, this represents a mean time between fatal crashes of more than 3 million vehicle hours of driving (representing 375 years of continuous driving 24 hours per day, 7 days per week) and a mean time between injury crashes of about 65,000 vehicle hours of driving (representing more than 7 years of continuous 24/7 driving). Those numbers are similar for most industrialized countries (within a factor of 2 above or below), and that poses severe challenges for a software-intensive system that must operate in a highly dynamic and stochastic environment.

Several serious technological challenges need to be conquered before automated driving systems will be able to safely operate without constant human supervision. These are summarized here, in order of increasing difficulty, and are described in more detail in Shladover (2014) and Shladover and Bishop (2015).

1. Providing the automated driving system with comprehensive fault detection, identification, and accommodation capabilities so that it can immediately diagnose its own malfunctions and switch to a fallback mode of operation that can maintain safety even if it needs to sacrifice performance (such as significantly reducing speed and/or parking the vehicle on the shoulder of the road). This requires redundancy of hardware and software functionality, which is bound to increase costs of development and implementation.
2. Ensuring sufficient cybersecurity protection to repel the large majority of cyberattacks. This is already becoming a challenge for modern nonautomated vehicles because of their dependence on electromechanical actuation (engine, brake, and steering control) and in-vehicle networks, but the temptation for attackers is likely to be greater for highly automated vehicles, whose occupants are less likely to notice and respond quickly to an attack (because they are not doing the driving).
3. Developing comprehensive environment perception capabilities that can reliably identify, track, and discriminate between benign and hazardous objects in the path of the vehicle under the full range of environmental conditions in which the vehicle is intended to operate (weather and lighting conditions). Essentially all hazardous objects must be recognized, even if they are difficult to perceive from a long enough range to enable the system or the driver to

take corrective action (potholes, rocks, or bricks in the path of the vehicle's tires, and so forth). At the same time, the system must be intelligent enough to ignore nearly all benign objects (paper bags, balloons, newspapers, and so forth) even if they are highly visible so that the vehicle does not take spurious avoidance maneuvers, which will disconcert the vehicle occupants and could potentially cause new crashes. This is likely to require the fusion of data from multiple sensors that are based on different phenomenology and are not vulnerable to common-mode faults, which has cost implications.

4. Resolving questions of "robot ethics" sufficiently to enable the system software to make "life or death" decisions affecting the safety of all road users. Even if the environment perception software obtains "perfect" knowledge of the environment surrounding the vehicle, it will still be confronted with questions about which target objects to hit when a crash is unavoidable, and the complexity of those decisions is magnified when the knowledge of those objects is confounded by uncertainties. This could be one of the first instances in which software is entrusted with the authority to make life-or-death judgments about multiple people, yet there are no established ground rules for making such judgments ethically or even for managing the design process. Similarly, ethical conundrums arise when practical considerations of driving in imperfect traffic conditions conflict with strict interpretations of traffic law regarding speeds, crossing lane boundaries, and so forth. More broadly, designers of automation systems need to be made aware that they are applying ethical considerations in their work even if they are not conscious of that, and it is much better to be making those value judgments consciously rather than unconsciously.
5. Designing a software-intensive system for a very high level of safety, so that the rate of errors in the system requirements, specifications, and coding is sufficiently low that the system will be no less safe than human driving. This is the most daunting of all the technological challenges because there is no existing technology that can support the design, development, verification, or validation of software of the level of complexity that will be needed for automated driving systems. Formal methods have been applied to much simpler software examples, but their complexity is such that they do not scale well to software of this complexity. The current methods of software verification and validation are very costly and labor intensive, even for applications that are much less complicated than automated driving (e.g., aircraft autopilots), and even those depend on a priori assumptions about the completeness of the software specifications, which cannot be ensured in this case.

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Abbreviations

DOE	U.S. Department of Energy
NHTSA	National Highway Traffic Safety Administration

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Appendix G

Potential Impacts of Climate Change on the Interstate Highway System

Donald J. Wuebbles and Jennifer M. Jacobs

INTRODUCTION

The Interstate Highway System in the United States is vital to the transport of people and goods across our country. As required in Section 6021 of the Fixing America's Surface Transportation Act of 2016, the Future Interstate Study will address the actions needed to upgrade and restore the Interstate Highway System as a premier system that meets the demands of the 21st century. In particular, Congress has asked that the Future Interstates Study consider a 50-year planning horizon. Over a time period of such duration, key trends critical to the analyses for this study need to be estimated.

Among the many stresses on the Interstate Highway System over the coming decades, one of the most important is the change occurring in Earth's climate system and how the associated changes in temperature, precipitation, and other climate-related parameters are likely to affect the United States. Earth's climate system includes the land surface, atmosphere, oceans, and ice. The world, including the United States, has warmed over the past 150 years, especially over the past six decades, and that warming has triggered many other changes in Earth's climate. Evidence for a changing climate abounds, from the top of the atmosphere to the depths of the oceans. Many thousands of studies conducted by thousands of scientists around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; disappearing snow cover; shrinking sea ice; rising sea levels; and increasing levels of atmospheric water vapor. Rainfall patterns and storms are changing, and the occurrence of droughts is shifting.

Earth's climate is changing at a pace and in a pattern not explainable by natural influences. Many different lines of evidence demonstrate that human activities, especially emissions of greenhouse gases, are primarily responsible for the observed climate changes in the industrial era, especially over the past six decades. Over the past century, there do not appear to be any plausible alternative explanations supported by the evidence that are either credible or that can contribute more than marginally to the observed patterns. Solar flux variations over the past six decades have been too small to explain the observed changes in climate (Bindoff et al. 2013). The observational record also does not indicate any natural cycles that can explain the recent changes in climate (e.g., Marcott et al. 2013; PAGES 2K Consortium 2013). Natural cycles within Earth's climate system can only redistribute heat; they cannot be responsible for the observed increase in the overall heat content of the climate system (Church et al. 2011). Any explanations for the observed changes in climate must be grounded in understood physical mechanisms, appropriate in scale, and consistent in timing and direction with the long-term observed trends. Known human activities quite reasonably explain what has happened without the need for other factors. Internal variability and natural forcing factors cannot explain what is happening and there are no suggested factors, even speculative ones, that can explain the timing or magnitude, and that would somehow cancel out the role of human factors (Anderson et al. 2012).

People throughout the world are already feeling the effects of climate change—going well beyond an increasing temperature—especially from increasing intensity of certain types of extreme weather and from sea level rise that are fueled by the changing climate. Prolonged periods of heat and heavy downpours, and in some regions, floods and in others, drought, are affecting human health, agriculture, water resources, energy, transportation infrastructure, and much more. Almost every facet of our lives is being or likely will be affected by the changes occurring in climate, including potential effects on the types and quantity of food we eat, where we live, the types of available jobs, and, critically, how people and goods move.

Like other sectors of our society, the transportation sector and the Interstate System are vulnerable to the changes occurring in climate. The consensus finding from the U.S. transportation sector is that the nation's transportation systems and networks will be affected by changes in temperature, precipitation, and sea levels and that these changes may threaten or enhance transportation performance at the facility, system, and national levels. The most relevant potential climate change impacts to transportation infrastructure are increases in intense precipitation events, increases in Arctic temperatures (leading to permafrost melting), rising sea levels, increases in very hot days and heat waves, and increases in hurricane intensity (Burbank 2012; Caltrans 2013; CNA Military Advisory Board

2014; MacArthur et al. 2012; U.S. DOT 2014). Climate stressors affect Interstate System activities including operations and maintenance, design, and long-term planning.

Our understanding of how climate change affects the nation's transportation systems is largely informed by studies conducted over just the past 10 years (Savonis et al. 2014). These assessments primarily use national climate reports (e.g., IPCC 2014; Melillo et al. 2014; TRB 2014) and sea level rise assessments, but also use climate change information generated by regional and local climate scientists (Douglas et al. 2017). In that brief period, significant progress has been made in understanding the vulnerability of transportation assets and impacts to system performance. Furthermore, new tools, methods, and frameworks are emerging that can improve the consistency of exposure and sensitivity assessments and, to a lesser extent, inform adaptation strategies and guide resource allocation decisions. To date, climate change assessments and adaptation are rarely included in transportation agencies' decision-making processes. Given the long lifetime of Interstate System assets, effective resource investment and strategies would be well served by considering the likely effects on the Interstate Highway System from climate change. Additionally, because the nation's transport system is highly interdependent, there are also secondary impacts to the Interstate System from climate change—performance impacts to local roadways, public transportation, rail, air, pipelines, and maritime and port facilities (Caltrans 2013; CNA Military Advisory Board 2014; Johnson 2012; TRB 2014; U.S. DOT 2015). Beyond transportation, essential products and services such as energy, food, manufacturing, and trade all depend in interrelated ways on the reliable functioning of our nation's transportation system, including the Interstate Highway System.

OUR CHANGING CLIMATE

Climate is defined as long-term averages and variations in weather measured over multiple decades. Predicting how climate will change in future decades is a different scientific issue from predicting weather a few weeks from now. Local weather is short term, with limited predictability, and is determined by the complicated movement and interaction of high-pressure and low-pressure systems in the atmosphere; thus, it is difficult to forecast day-to-day changes beyond a week currently or up to about 2 weeks eventually. Climate is the statistics of weather—meaning not just average values but also the prevalence and intensity of extremes—as observed over a period of decades. There are clear effects of physical factors (e.g., latitude, mountains, distance to the coast) on the statistical character of the weather. As a result, the statistical properties are a result of the physical processes and conditions present and are readily predicted. Climate emerges from the interaction, over time, of rapidly changing local weather and more slowly changing regional and global influences, such as the distribution of heat in the oceans, the amount of energy reaching Earth from the Sun, and the composition of the atmosphere.

Observed Trends in Temperature

Highly diverse types of measurements made on land, sea, and in the atmosphere over many decades have allowed scientists to conclude with confidence that global mean temperature is increasing. Global annual average temperature, as measured over both land and oceans (used interchangeably with global average temperature in the discussion below), has increased by more than 1.7°F (0.9°C) over the entire period (see Figure G-1); see Vose and colleagues (2012) for discussion on how global annual average temperature is derived by scientists. Global average temperature is not expected to increase smoothly over time in response to the human warming influences, because the warming trend is superimposed on natural variability associated with, for example, the El Niño/La Niña ocean-heat oscillations and the cooling effects of particles emitted by volcanic eruptions. Even so, 16 of the top 17 warmest years in the instrumental record (since the late 1800s) occurred in the period from 2001 to 2016 (1998 was the exception). Global average temperature for 2016 surpassed 2015 by a small amount as the warmest year on record. The year 2015 far surpassed 2014 by 0.29°F (0.16°C), four times greater than the difference between 2014 and the next warmest year, 2010 (NCEI 2016a). In addition, looking at longer time scales, every decade since 1956–1965 has been warmer than the previous decade (see Figure G-2).

Although there has been widespread warming over the past century, not every region has warmed at the same pace (see Figure G-3). Warming during the first half of the 1900s occurred mostly in the Northern Hemisphere (Delworth and Knutson 2000). Recent decades have seen greater warming, particularly at high northern latitudes, and over land compared to the ocean. In general, winter is warming faster than summer (especially in northern latitudes). Also, nights are warming faster than days (Alexander et al. 2006; Davy et al. 2016). There is also some evidence of faster warming at higher elevations (Mountain Research Initiative 2015). Even in the absence of significant ice melt, the ocean is expected to warm more slowly given its larger heat capacity, leading to land–ocean differences in warming. As a result, the climate for land areas often responds more rapidly than the ocean areas, even though the forcing driving a change in climate occurs equally over land and the oceans (IPCC 2013).

A few regions, such as the North Atlantic Ocean, have experienced cooling over the past century, though these areas have warmed over recent

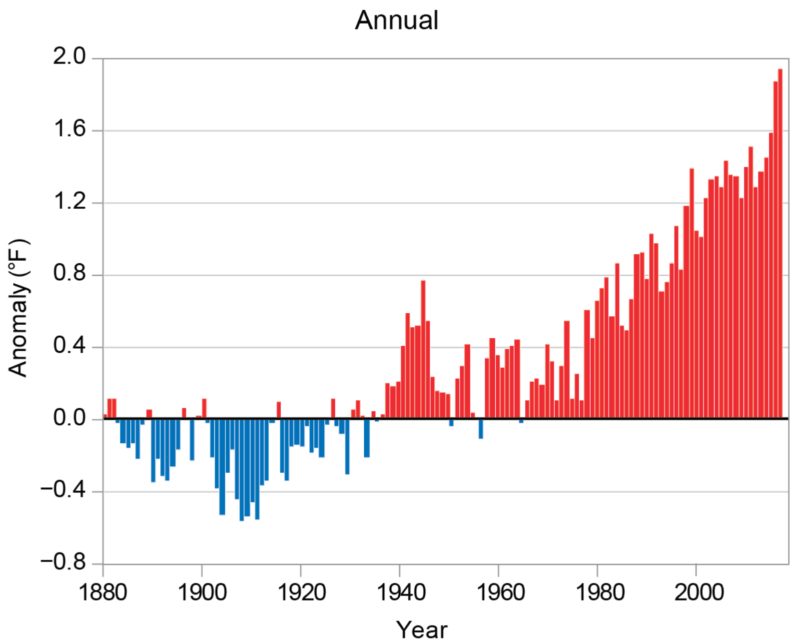


FIGURE G-1 Global annual average temperatures (as measured over both land and oceans) for 1880–2016 relative to the reference period of 1901–2000.
NOTES: Red bars indicate temperatures above the average over 1901–2000 and blue bars indicate temperatures below the average. Global annual average temperature has increased by more than 1.7°F (0.9°C) over the entire period. Although there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are mainly due to natural sources of variability, such as the effects of El Niño, La Niña, and volcanic eruptions.
SOURCE: Based on the National Centers for Environmental Information (NOAA-GlobalTemp) data set (updated from Vose et al. 2012).

decades. Regional climate variability is important (e.g., Hoegh-Guldberg et al. 2014; Hurrell and Deser 2009), as are the effects of the increasing freshwater in the North Atlantic from melting of sea and land ice (Rahmstorf et al. 2015).

The average annual temperature of the contiguous United States has risen since the start of the 20th century. In general, temperature increased until about 1940, decreased until about 1970, and increased rapidly through 2016. Because the increase was not constant over time, multiple methods were evaluated to quantify the trend. All methods yielded rates of warming that were significant at the 95 percent level. The lowest estimate

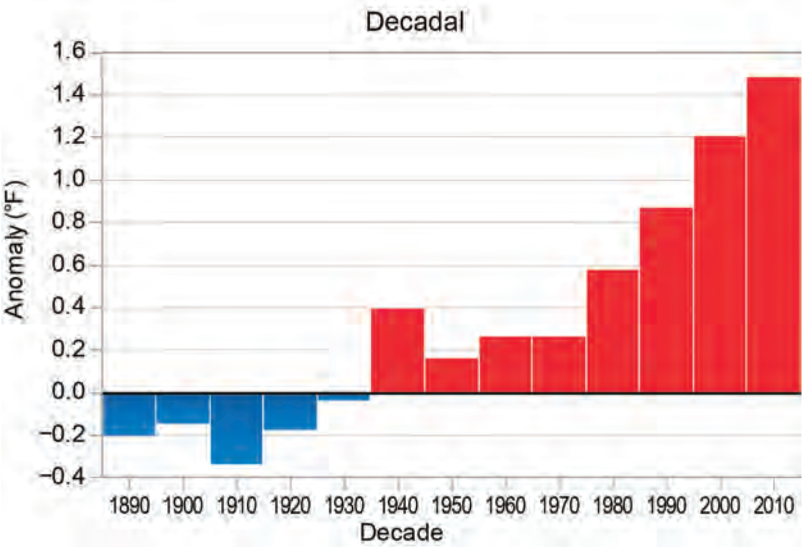


FIGURE G-2 Global average temperature averaged over decadal periods (1886–1895, 1896–1905, ..., 1996–2005, except for the 11 years in the last period, 2006–2016) relative to the reference period of 1901–2000.
NOTES: Red bars indicate temperatures above the average over 1901–2000 and blue bars indicate temperatures below the average. Horizontal label indicates midpoint year of decadal period. Every decade since 1956–1965 has been warmer than the previous decade.
SOURCE: Based on the National Centers for Environmental Information (NOAA-GlobalTemp) data set (NCEI 2016b).

of 1.2°F (0.7°C) was obtained by computing the difference between the average for 1986–2016 (i.e., present day) and the average for 1901–1960 (i.e., the first half of the last century). The highest estimate of 1.8°F (1.0°C) was obtained by fitting a linear (least-squares) regression line through the period 1895–2016.

More than 95 percent of the land surface of the contiguous United States has had an increase in average annual temperature (see Figure G-4). In contrast, only small (and somewhat dispersed) parts of the Southeast and Southern Great Plains experienced cooling. From a seasonal perspective, warming was greatest and most widespread in winter, with increases of more than 1.5°F (0.8°C) in most areas. In summer, warming was less extensive (mainly along the East Coast and in the western third of the nation), while cooling was evident in parts of the Southeast, Midwest, and Great Plains.

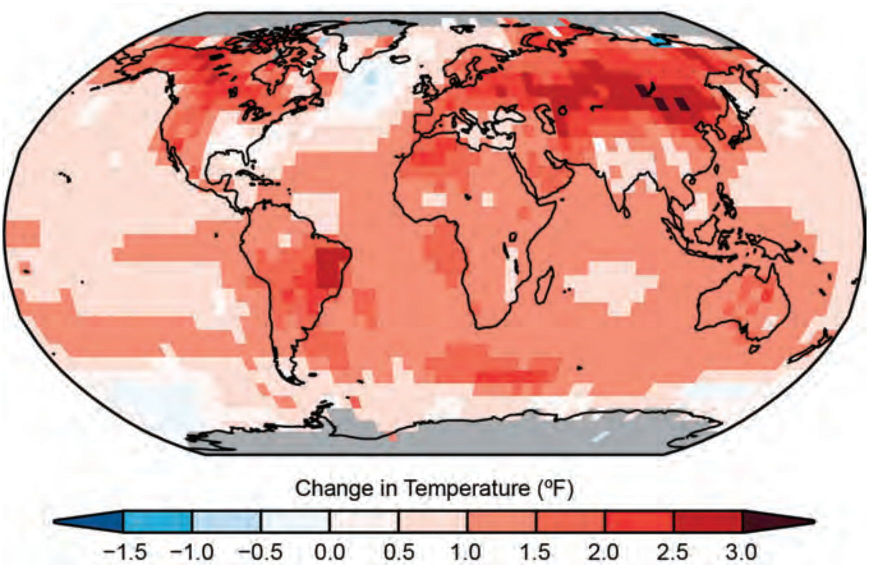


FIGURE G-3 Surface temperature change for the period 1986–2015 relative to 1901–1960.
NOTES: For visual clarity, statistical significance is not depicted on this map. Changes are generally significant (at the 90 percent level) over most land and ocean areas. Changes are not significant in parts of the North Atlantic Ocean, the South Pacific Ocean, and the southeastern United States. There are insufficient data on the Arctic Ocean and Antarctica for computing long-term changes. The relatively coarse resolution (5.0° × 5.0°) of these maps does not capture the finer details associated with mountains, coastlines, and other small-scale effects.
SOURCE: Based on the National Centers for Environmental Information (NOAA-GlobalTemp) data set (updated from Vose et al. 2012).

Other Indicators of Climate Change

Observational data sets for many other climate variables support the conclusion with high confidence that the global climate (including that of the United States) is changing (Blunden and Arndt 2016; EPA 2016a; Meehl et al. 2016). Not only have temperatures in the lower atmosphere increased, but so have ocean temperatures. Basic physics tells us that a warmer atmosphere can hold more water vapor; increasing atmospheric humidity is exactly what is measured from satellite data. At the same time, the warmer world should result in higher evaporation rates and major changes to the hydrological cycle, including observed increases in the prevalence of torrential downpours. Multiple observational data sets show that the heat content of the oceans is increasing and that sea levels are rising. Arctic sea

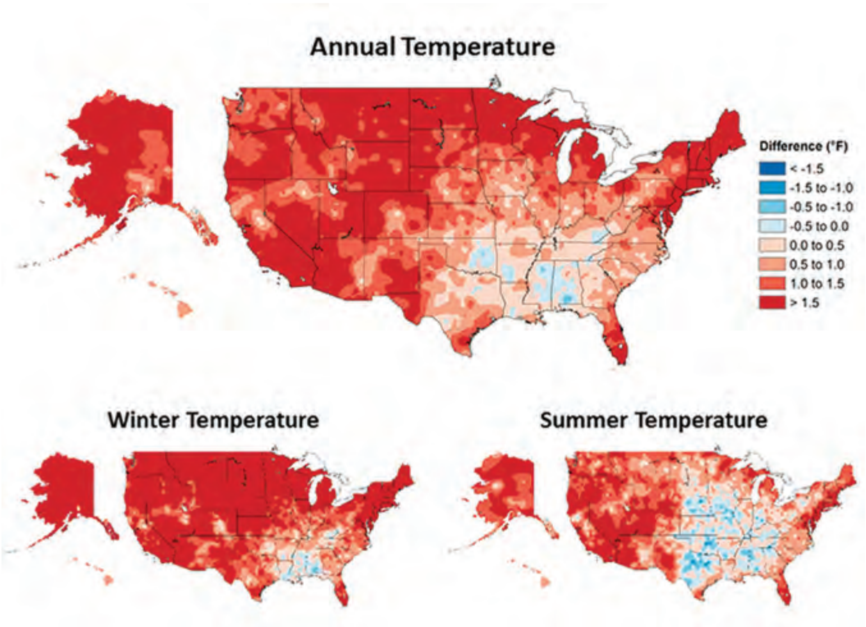


FIGURE G-4 Observed changes in annual, winter, and summer temperature.
NOTE: Changes are the difference between the average for present day (1986–2016) relative to 1901–1960 for the contiguous United States, and relative to 1925–1960 for Alaska and Hawaii.
SOURCE: Adapted from Vose et al. 2014a, 2017.

ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. The relatively small increase in Antarctic sea ice in the 15-year period from 2000 through early 2016 appears to be best explained as being due to localized natural variability (see, e.g., Meehl et al. 2016; Ramsayer 2014); while possibly also related to natural variability, the 2017 Antarctic sea ice minimum reached in early March was the lowest measured since reliable records began in 1979. The vast majority of the glaciers in the world are losing mass at significant rates. The two largest ice sheets on our planet—on the land masses of Greenland and Antarctica—are shrinking. There are a number of other climate indicators (e.g., see EPA [2016a] for a discussion of other indicators such as changes in the growing season and the allergy season). The observational data sets all paint a consistent and convincing picture that the climate of our planet is warming.

Observed Trends in Precipitation

Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for more than a century. However, spatial scales of precipitation are small (e.g., it can rain several inches in Washington, DC, but not a drop in nearby Baltimore) and this makes interpretation of the point measurements difficult. Annual average precipitation across global land areas (see Figure G-5) exhibits a slight rise (which is not statistically significant because of a lack of data coverage early in the record) over the past century along with ongoing increases in atmospheric moisture levels. Interannual and interdecadal variability is clearly found in all precipitation evaluations. There are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude regions taken as a whole. Stronger trends are generally found over the past four decades.

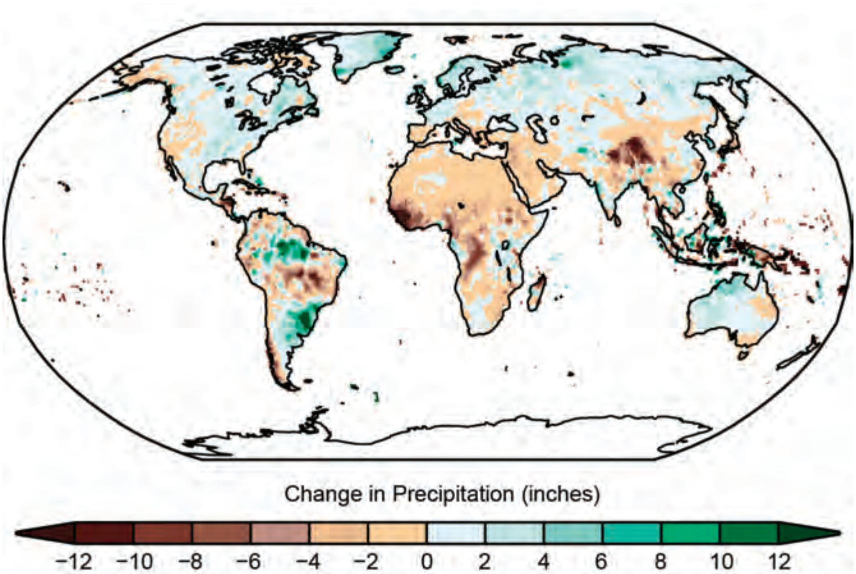


FIGURE G-5 Surface annually averaged precipitation change for the period 1986–2015 relative to 1901–1960.
NOTE: The data are from long-term stations, and so precipitation changes over the ocean and Antarctica cannot be evaluated. The trends are not considered to be statistically significant because of a lack of data coverage early in the record. The relatively coarse resolution (0.5° × 0.5°) of these maps does not capture the finer details associated with mountains, coastlines, and other small-scale effects.
SOURCES: NOAA National Centers for Environmental Information (NCEI) and Cooperative Institute for Climate and Satellites.

Annual precipitation averaged across the United States has increased approximately 4 percent over the 1901–2015 period. There continue to be important regional and seasonal differences in precipitation changes (see Figure G-6). Regional differences are apparent, as the Northeast, Midwest, and Great Plains have had increases while parts of the Southwest and Southeast have had decreases. The lingering droughts in the western and southwestern United States were an important part of this (Barnston and Lyon 2016; NCEI 2016a). However, for now, the meteorological drought

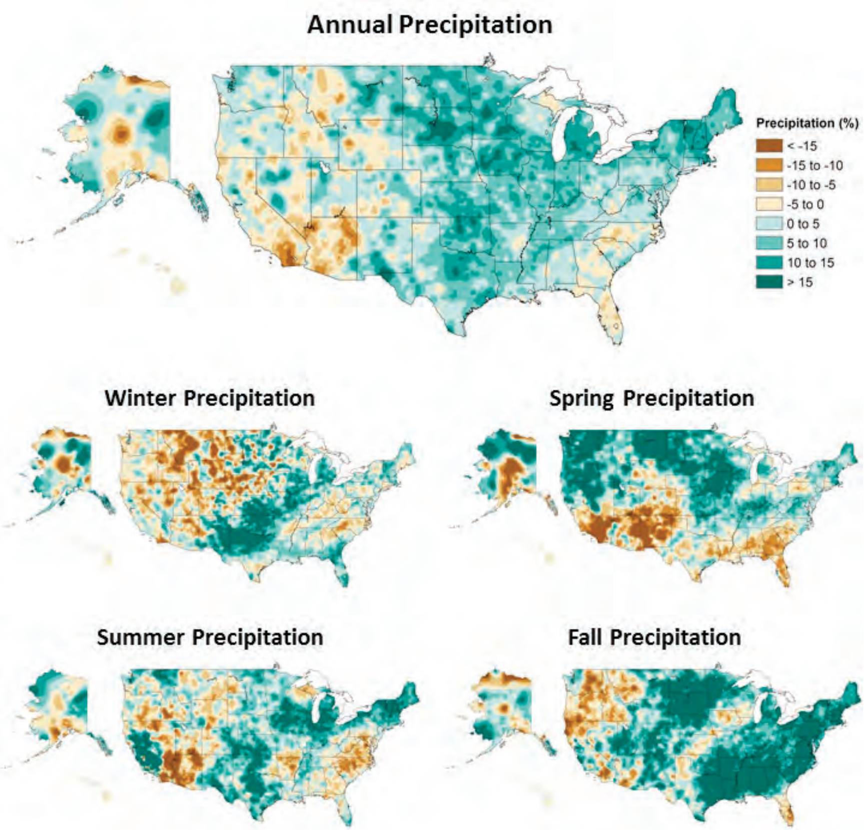


FIGURE G-6 Annual and seasonal changes in precipitation derived from observations over the contiguous United States.
NOTE: Changes are the average for present day (1986–2015) minus the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and Hawaii) divided by the average for the first half of the century.
SOURCE: Data from NOAA National Centers for Environmental Information (NCEI) nCLIMDiv data set.

in California that began in late 2011 (NCEI 2016a; Seager et al. 2015) appears to be largely over, due to the substantial precipitation and snowpack the state received in winter 2016–2017 that greatly increased reservoirs. For the United States, the year 2015 was the third wettest on record, just behind 1973 and 1983 (all of which were years marked by El Niño events). Interannual variability is substantial, as evidenced by large multiyear meteorological and agricultural droughts in the 1930s and 1950s.

Seasonally, national increases are largest in the fall, while little change is observed for winter (NCEI 2016a). For the contiguous United States, fall exhibits the largest (10 percent) and most widespread increase, exceeding 15 percent in much of the Northern Great Plains, Southeast, and Northeast. Winter has the smallest increase (2 percent), with drying over most of the western United States as well as parts of the Southeast.

Changes in snow cover extent (SCE) in the Northern Hemisphere exhibit a strong seasonal dependence (Vaughan et al. 2013). There has been little change since the 1960s (when the first satellite records became available) in the winter, while fall SCE has increased. However, the decline in spring SCE is larger than the increase in fall and is due in part to higher temperatures that shorten the time that snow spends on the ground in the spring.

An analysis of seasonal maximum snow depth for 1961–2015 over North America indicates a statistically significant downward trend (of 0.11 standardized anomalies per decade) and a trend toward the seasonal maximum snow depth occurring earlier—approximately 1 week earlier on average since the 1960s (Kunkel et al. 2016). There has been a statistically significant decrease over the period of 1930–2007 in the frequency of years with a large number of snowfall days (years exceeding the 90th percentile) in the southern United States and the U.S. Pacific Northwest and an increase in the northern United States (Kluver and Leathers 2015). In the snow belts of the Great Lakes, lake-effect snowfall has increased overall since the early 20th century for Lakes Superior, Michigan, Huron, and Erie (Kunkel et al. 2010). However, individual studies for Lake Michigan (Bard and Kristovich 2012) and Lake Ontario (Hartnett et al. 2014) indicate that this increase has not been continuous. In both cases, upward trends were observed until the 1970s and early 1980s. However, since then lake-effect snowfall has decreased in these regions. Lake-effect snows along the Great Lakes are affected greatly by ice cover extent and lake water temperatures. As ice cover diminishes in winter, the expectation is for more lake-effect snow until temperatures increase enough that much of what now falls as snow instead falls as rain (Vavrus et al. 2013; Wright et al. 2013).

End-of-season snow water equivalent (SWE)—especially important where water supply is dominated by spring snow melt (e.g., in much of the American West)—has declined since 1980 in the western United States, based on analysis of in situ observations, and is associated with springtime warming (Pederson et al. 2013). Satellite measurements of SWE based on brightness temperature also show a decrease over this period (Gan et al. 2013).

Observed Changes in Severe Weather

Along with the overall changes in climate, there is strong evidence of an increasing trend over recent decades in some types of extreme weather events, including their frequency, intensity, and duration, with resulting impacts on our society. It is becoming clearer that the changing trends in severe weather are already affecting us greatly.

A change in the frequency, duration, and/or magnitude of extreme weather events is one of the most important consequences of a warming climate. A small shift in the mean of a weather variable, with or without this shift occurring in concert with a change in the shape of its probability distribution, can cause a large change in the probability of a value relative to an extreme threshold (Katz and Brown 1992; see also IPCC 2013, Figure 1.8). Examples include extreme high-temperature events and heavy-precipitation events. Additionally, extreme events such as intense tropical cyclones, mid-latitude cyclones, and hail and tornadoes associated with thunderstorms, can occur as isolated events that are not generally studied in terms of extremes within a probability distribution. Detecting trends in the frequency and intensity of extreme weather events is challenging (Sardeshmukh et al. 2015). The most intense events are rare by definition, and observations may be incomplete and suffer from reporting biases. For some events, such as those relating to temperature and precipitation extremes, there is strong understanding of the trends and the underlying causes of the changes (e.g., IPCC 2012, 2013; Kunkel et al. 2013a, 2013b; Peterson et al. 2013; Stott 2016; Vose et al. 2014a, 2014b; Wuebbles et al. 2014b).

Through 2016, the United States has sustained 203 weather/climate disasters due to severe weather events since 1980 for which damages/costs reached or exceeded $1 billion per event (including Consumer Price Index adjustment to 2016 to account for inflation), with an overall increasing trend (NCES 2018; see also Smith and Katz 2013). The total cost of these 203 events over the 36 years is more than $1.1 trillion. The year 2016 had 15 such events, costing the United States $46 billion in damages and resulting in 138 fatalities. As of April 6, 2017, there were five events with losses exceeding $1 billion each across the United States. As seen in Figure G-7, the number of U.S. billion-dollar events has increased from about three such events per year in the decade of the 1980s to more than 10 events per year over the past decade; costs per event have also more than doubled.

Every U.S. state has been affected by the billion-dollar events. The events in these analyses include major heat waves, severe storms, tornadoes,

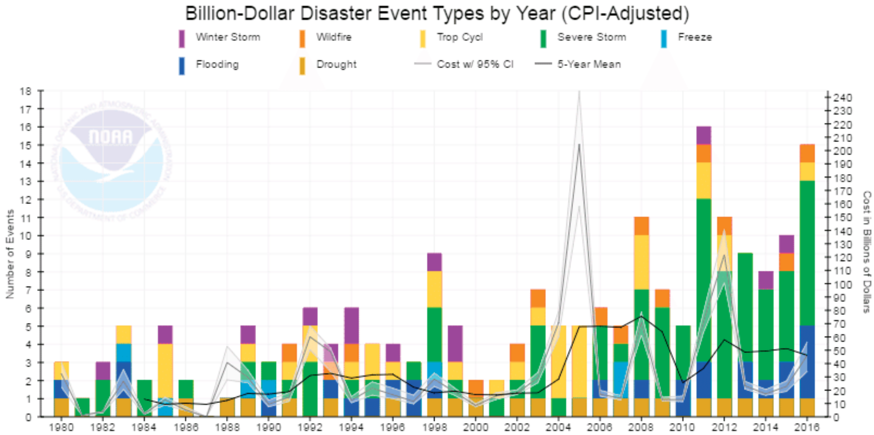


FIGURE G-7 Increasing trend in number of severe loss events in the United States from natural catastrophes per year since 1980 through 2016 by type of event.
NOTES: NOAA has tracked such billion-dollar events since 1980. The costs for each year and the 5-year running mean of costs are also shown.
SOURCE: Adapted from NCEI 2018.

droughts, floods, hurricanes, and wildfires. A portion of these increased costs can be attributed to the increase in population and infrastructure near coastal regions. However, even if hurricanes and their large, mostly coastal, impacts were excluded, there still would be an overall increase in the number of billion-dollar events over the past 34 years. Similar analyses by Munich Re[1] and other organizations come to similar conclusions, finding that there are growing numbers of severe weather events worldwide causing extensive damage and loss of lives. In summary, there is a clear trend in the impacts of severe weather events on human society in the United States and throughout the world.

Changing trends in some types of extreme weather events have been observed in recent decades. Modeling studies indicate that these trends are consistent with the changing climate. Much of the world is being affected by changing trends in extreme events, including increases in the number of extremely hot days, fewer extreme cold days, more precipitation events coming as unusually large precipitation, and more floods in some regions and more drought in others (IPCC 2012, 2013; Melillo et al. 2014; Min et al. 2011, 2013; Wuebbles et al. 2014a, 2014b; Zwiers et al. 2013). High-impact, large-scale extreme events are complex phenomena involving various factors that come together to create a "perfect storm." Such extreme

[1] See https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/overview-natural-catastrophe-2016.html.

weather obviously does occur naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events. Observed trends in extreme weather events, such as more hot days, fewer cold days, and more precipitation coming as extreme events, are expected to continue and to intensify over this century.

The frequency of extreme high temperatures at both daytime and nighttime hours and multiday heat waves is increasing over many of the global land areas (IPCC 2013). There are increasing areas of land throughout our planet experiencing an excess number of daily highs above given thresholds (e.g., the 90th percentile), with an approximate doubling since 1998 of the world's land area with 30 extreme heat days per year (Seneviratne et al. 2014). At the same time, frequencies of cold waves and extremely low temperatures are decreasing over much of the world, including the United States. The number of record daily high temperatures in the United States has been about double the number of record daily low temperatures in the 2000s (Meehl et al. 2009), and much of the United States has experienced decreases of 5 to 20 percent per decade in cold-wave frequency (Easterling et al. 2016; IPCC 2013). The enhanced radiative forcing caused by greenhouse gases has a direct influence on heat extremes by shifting distributions of daily temperature (Min et al. 2013).

The meteorological situations that cause heat waves are a natural part of the climate system. Thus, the timing and location of individual events may be largely a natural phenomenon, although even these may be affected by human-induced climate change (Trenberth and Fasullo 2012; Trenberth et al. 2015). However, there is emerging evidence that most of the increasing heat-wave severity over our planet is likely related to the changes in climate, with a detectable human influence for major recent heat waves in the United States (Duffy and Tebaldi 2012; Meehl et al. 2009; Rupp et al. 2012, 2013), Europe (Stott et al. 2010; Trenberth 2011), and Russia (Christidis et al. 2011). As an example, the summer 2011 heat wave and drought in Oklahoma and Texas, which cost Texas an estimated $8 billion in agricultural losses, was primarily driven by precipitation deficits, but the human contribution to climate change approximately doubled the probability that the heat was record-breaking (Hoerling et al. 2013). So while an event such as this Texas heat wave and drought could be triggered by a naturally occurring event such as a deficit in precipitation, the chances for record-breaking temperature extremes have increased and will continue to increase as the global climate warms. Generally, the changes in climate are increasing the likelihood for these types of severe events.

In most of the world, including the United States, over the past three decades, the heaviest rainfall events have become more frequent (e.g., Figure G-8 gives percentage changes in the top 1 percent of rainfalls over various regions of the United States and Figure G-9 shows the changing trend

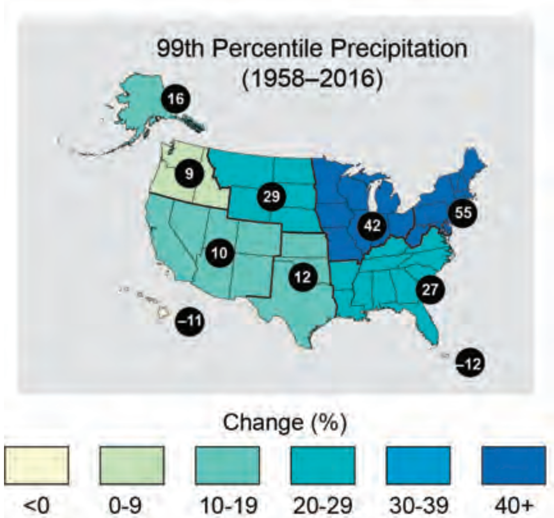


FIGURE G-8 Change in the amount of extreme precipitation falling in daily events that exceed the 99th percentile of all non-zero precipitation days, by region of the United States.
NOTES: The numerical value is the percentage change over the entire period, 1958–2016. The percentages are first calculated for individual stations, then averaged over 2° latitude by 2° longitude grid boxes, and finally averaged over each region.
SOURCES: Cooperative Institute for Climate and Satellites and National Oceanic and Atmospheric Administration National Centers for Environmental Information.

nationally in the 2-day precipitation events exceeding the station-specific threshold for a 5-year recurrence interval, i.e., the one-in-5-year events). When there is precipitation, the amount falling in very heavy precipitation events has been significantly above average. This increase has been greatest in the Northeast, Midwest, and upper Great Plains. Because basic physics tells us that a warmer atmosphere should generally hold more water vapor, this finding is not so surprising. Analyses indicate that these trends will continue (Janssen et al. 2014, 2016; Melillo et al. 2014; Wuebbles et al. 2014a, 2014b).

Detection and attribution of trends in past tropical cyclone activity, referred to as hurricanes when they occur in the Atlantic Ocean, are hampered by uncertainties in the data collected prior to the satellite era and by uncertainty in the relative contributions of natural variability and anthropogenic influences. Whether global trends in high-intensity tropical cyclones are already observable is a topic of active debate. Some research suggests positive trends (Elsner et al. 2008; Kossin et al. 2013), but significant uncertainties remain (Kossin et al. 2013). There has been no significant trend in the global number of tropical cyclones (IPCC 2012, 2013) nor has any

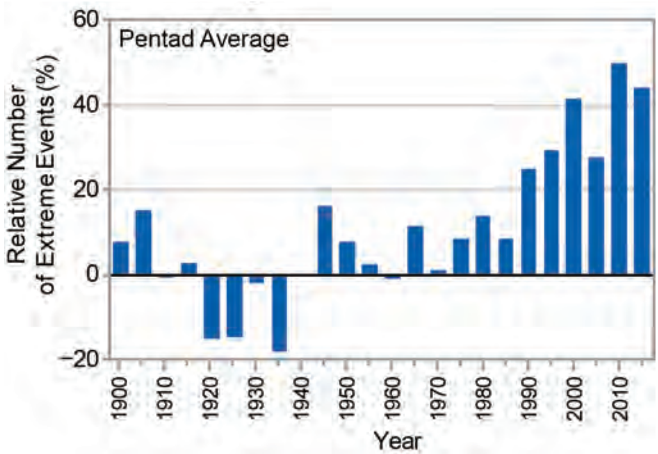


FIGURE G-9 Index of the number of 2-day precipitation events exceeding the station-specific threshold for a 5-year recurrence interval, expressed as a percentage difference from the 1901–1960 mean.
NOTES: The annual values are averaged over 5-year periods, with the pentad label indicating the ending year of the period. Annual time series of the number of events are first calculated at individual stations. Next, the grid box time series are calculated as the average of all stations in the grid box. Finally, a national time series is calculated as the average of the grid box time series.
SOURCES: Cooperative Institute for Climate and Satellites and National Oceanic and Atmospheric Administration National Centers for Environmental Information; data from Global Historical Climatology Network-Daily.

trend been identified in the number of U.S. landfalling hurricanes (Melillo et al. 2014). Recent evidence indicates that the locations where tropical cyclones reach their peak intensity have migrated poleward in both the Northern and Southern Hemispheres, in concert with the independently measured expansion of the tropics (Kossin et al. 2014). A number of recent studies suggest that hurricane intensities are expected to increase with climate change, both on average and at the high end of the scale, as the range of achievable intensities expands, so that the most intense storms will exceed the intensity of any in the historical record (Sobel et al. 2016).

Trends remain uncertain in some types of severe weather, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, but such events are under scrutiny to determine if there is a climate change influence. Increasing air temperature and moisture increase the risk of extreme convection, and there is evidence for a global increase in severe thunderstorm conditions (Sander et al. 2013). Strong convection along with wind shear represent favorable conditions for tornadoes. Initial studies do suggest that tornadoes could get more intense in the coming decades (Diffenbaugh et al. 2013).

Observed Trends in Sea Level

Sea level rise is closely linked to increasing global temperatures. Thus, even as uncertainties remain about just how much sea level may rise this century, it is virtually certain that sea level rise this century and beyond will pose a growing challenge to coastal communities, infrastructure, and ecosystems from increased (permanent) inundation, more frequent and extreme coastal flooding, erosion of coastal landforms, and saltwater intrusion within coastal rivers and aquifers.

Sea level change is affected by a variety of mechanisms operating at different spatial and temporal scales (e.g., see Kopp et al. 2015). Global mean sea level (GMSL) rise is primarily driven by two factors: (1) increased volume of seawater due to thermal expansion of the ocean as it warms and (2) increased mass of water in the ocean due to melting ice from mountain glaciers and the Antarctic and Greenland ice sheets (Church et al. 2013). The overall amount (mass) of ocean water, and thus sea level, is also affected to a lesser extent by changes in global land-water storage, which reflects changes in the impoundment of water in dams and reservoirs and river runoff from groundwater extraction, inland sea and wetland drainage, and global precipitation patterns, such as occurs during phases of the El Niño–Southern Oscillation (ENSO) (Church et al. 2013; Reager et al. 2016; Rietbroek et al. 2016; Wada et al. 2016, 2017).

Sea level and its changes are not uniform globally for several reasons. First, atmosphere–ocean dynamics—driven by ocean circulation, winds, and other factors—are associated with differences in the height of the sea surface, as are differences in density arising from the distribution of heat and salinity in the ocean. Changes in any of these factors will affect sea surface height. For example, a weakening of the Gulf Stream transport in the mid- to late 2000s may have contributed to enhanced sea level rise in the ocean environment extending to the northeastern U.S. coast (Boon 2012; Ezer 2013; Sallenger et al. 2012), a trend that many models project will continue into the future (Yin and Goddard 2013; also see later discussion on the projections of sea level rise).

Second, the locations of land ice melting and land water reservoir changes impart distinct regional "static-equilibrium fingerprints" on sea level, based on gravitational, rotational, and crustal deformation effects (Mitrovica et al. 2011). For example, sea level falls near a melting ice sheet because of the reduced gravitational attraction of the ocean toward the ice sheet; reciprocally, it rises by greater than the global average far from the melting ice sheet.

A variety of other factors can cause local vertical land movement. These include natural sediment compaction, compaction caused by local extraction of groundwater and fossil fuels, and processes related to plate tectonics, such as earthquakes and more gradual seismic creep (Wöppelmann and Marcos 2016; Zervas et al. 2013).

After at least 2,000 years of little change, the world's average sea level rose by about 0.2 meters (8 inches) over the past century, and satellite data provide evidence that the rate of rise since 1993 has roughly doubled. Three inches (about 7 centimeters) of the increase has occurred since 1993.

The world's oceans are currently absorbing more than a quarter of the atmospheric carbon dioxide (CO_2) emitted to the atmosphere annually (Le Quéré et al. 2016) from human activities, largely from fossil fuel burning, making them more acidic, with potential detrimental impacts on marine ecosystems (Melillo et al. 2014). In particular, higher-latitude systems typically have a lower buffering capacity against pH change, exhibiting seasonally corrosive conditions sooner than low-latitude systems. Acidification is regionally increasing along U.S. coastal systems as a result of upwelling (e.g., in the Pacific Northwest), changes in freshwater inputs (e.g., in the Gulf of Maine), and nutrient input (e.g., in urbanized estuaries). The rate of acidification is unparalleled in at least the past 66 million years (Hönisch et al. 2012; Zeebe et al. 2016).

THE BASIS FOR PROJECTING FUTURE CHANGES IN CLIMATE

Earth's climate has long been known to change in response to natural external factors, termed climate forcings. These include variations in the energy received from the Sun, volcanic eruptions, and changes in the Earth's orbit, which affects the distribution of sunlight across the world. Earth's climate is also affected by factors that are internal to the climate system, which are the result of complex interactions among the atmosphere, ocean, land surface, and living things. These internal factors include natural modes of climate system variability, such as those that form El Niño events in the Pacific Ocean.

The temperature of the Earth system is determined by the amounts of incoming (short-wavelength) and outgoing (both short- and long-wavelength) radiation. Over recent decades, these fluxes have been well constrained from analyses of satellite measurements (IPCC 2013; Trenberth et al. 2009). About one-third (29.4 percent) of incoming, short-wavelength energy from the Sun is reflected back to space, and the remainder is absorbed by the Earth system. The fraction of sunlight scattered back to space is largely determined by the high reflectivity (albedo) of clouds, some land surfaces (especially those covered by snow and ice), oceans, and particles in the atmosphere.

In addition to reflected sunlight, Earth loses energy through infrared (long-wavelength) radiation from the surface and atmosphere. Greenhouse gases (GHGs) in the atmosphere absorb most of this radiation, much of which is radiated back toward the surface where it is absorbed, further heating Earth; the remainder is emitted to space. The naturally occurring GHGs in Earth's atmosphere—principally water vapor, carbon dioxide (CO_2), and ozone—keep the near-surface air temperature about 60°F (33°C) warmer than it would be in their absence, assuming albedo is held constant (Lacis et al. 2010). Geothermal heat from Earth's interior, direct heating from energy production, and frictional heating through tidal flows also contribute to the amount of energy available for heating Earth's surface and atmosphere, but their total contribution is an extremely small fraction (<0.1 percent) of that due to net solar (short-wave) and infrared (long-wave) radiation (for these various forcings, see, e.g., Davies and Davies [2010]; Flanner [2009]; and Munk and Wunsch [1998]).

Natural changes in external forcings and internal factors have been responsible for past climate changes. At the global scale, over multiple decades, the impact of external forcings on temperature far exceeds that of internal variability (which is less than 0.5°F (Swanson et al. 2009). At the regional scale, and over shorter time periods, internal variability can be responsible for much larger changes in temperature and other aspects of climate. Today, however, the picture is very different. Although natural factors still affect climate, human activities are now the primary cause of the current warming: specifically, human activities that increase atmospheric levels of CO_2 and other heat-trapping gases and various particles that, depending on the type of particle, can have either a heating or cooling influence on climate.

The greenhouse effect is key to understanding how human activities affect Earth's climate. As the Sun shines on Earth, the planet heats up. Earth then radiates this heat back to space. Some gases, including H_2O, CO_2, ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), absorb some of the heat given off by Earth's surface and lower atmosphere. These heat-trapping gases then radiate energy back toward the surface, effectively trapping some of the heat inside the climate system. This greenhouse effect is a natural process, first recognized in 1824 by the French mathematician and physicist Joseph Fourier and confirmed by British scientist John Tyndall in a series of experiments starting in 1859.

Of all the GHGs, CO_2 has been undergoing the largest changes in concentration and is the gas of most concern to climate change. Measurements of CO_2 concentration in air trapped in ice cores indicate that the preindustrial concentration of CO_2 was approximately 280 ppm (parts per million). These data show that CO_2 concentrations fluctuated by ±10 ppm around 280 ppm for well over 1,000 years until the recent increase to the current concentration of more than 400 ppm, an increase that is greater than 40 percent. CO_2 emissions have grown in the industrial era primarily from fossil fuel combustion (i.e., coal, gas, oil), cement manufacturing, and land use change, for example, from deforestation (Ciais et al. 2013). This 400-ppm level of CO_2 has not been seen on Earth for more than 1 million years, well before the appearance of humans.

Although methane's atmospheric abundance is less than 0.5 percent that of CO_2 on a molecule-for-molecule basis, a molecule of methane is approximately 50 times more effective as a GHG in the current atmosphere than CO_2 (this largely results from the center of the important infrared absorption features already being saturated for CO_2). When this is combined with the large increase in its atmospheric concentration, methane becomes the second most important GHG of concern for climate change. Based on analyses of ice cores, the concentration of methane has more than doubled since preindustrial times. The current globally averaged atmospheric concentration of methane is about 1.8 ppm. Methane concentrations have primarily increased due to human activities, including agriculture, with livestock producing methane in their digestive tracts, and rice farming producing it via bacteria that live in the flooded fields; mining coal, extraction and transport of natural gas, and other fossil fuel–related activities; and waste disposal including sewage and decomposing garbage in landfills.

In 2014, transportation accounted for 26 percent of the total emissions of GHGs in the United States, with 96 percent of these emissions being CO_2 (EPA 2016b). Of these emissions, 61 percent are from light-duty vehicles (cars and light-duty trucks), 23 percent from medium- and heavy-duty trucks, and a few more percent from motorcycles and buses.

Other important GHGs with changing concentrations are nitrous oxide (N_2O) and various halocarbons. Nitrous oxide levels are increasing, primarily as a result of fertilizer use and fossil fuel burning. The concentration of nitrous oxide has increased by about 20 percent relative to preindustrial times. The major halocarbons are produced almost entirely by the chemical industry for a variety of uses (e.g., refrigeration).

Human activities can also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfur-containing particles reflect incoming sunlight away from Earth, exerting a cooling influence on Earth's surface. Another type of particle, composed mainly of soot, or black carbon, absorbs incoming sunlight and traps heat in the atmosphere, warming Earth. Changes in particle concentrations are also important in analyzing changes in climate. Particles both have a direct radiative effect on climate and an indirect effect through their effects in changing the properties of clouds. Overall, the net effect of these particles is to globally offset 20 percent to 35 percent of the warming caused by the increasing concentrations of GHGs.

It is not only the direct effects from human emissions that affect climate. These direct effects also trigger a cascading set of feedbacks that cause indirect effects on climate—acting to increase or dampen an initial change (Melillo et al. 2014). For example, water vapor is the single most important gas responsible for the natural greenhouse effect. Together, water vapor and clouds account for between 66 percent and 80 percent of the natural greenhouse effect (Schmidt et al. 2010). However, the amount of water vapor in the atmosphere depends on temperature; increasing temperatures increase the amount of water vapor. This means that the response of water vapor is an internal feedback, not an external forcing of the climate.

Some of the other important feedbacks include effects of changes in clouds, changes in albedo, and changes in CO_2 absorption by the oceans and the biosphere as the planet warms. Feedbacks are particularly important in the Arctic, where rising temperatures melt ice and snow, exposing relatively dark land and ocean that absorb more of the Sun's energy, heating the region even further. Rising temperatures also thaw permafrost, releasing CO_2 and methane trapped in the previously frozen ground into the atmosphere, where they further amplify the greenhouse effect. Both of these feedbacks act to further amplify the initial warming effects from GHGs. Together, these and other feedbacks determine the long-term response of Earth's temperature to an increase in CO_2 and other emissions from human activities. Scientific analyses largely indicate a significant overall amplification of the warming effect as a result of the feedbacks (IPCC 2013; Melillo et al. 2014).

The conclusion that human influences are the primary driver of recent climate change is based on multiple lines of independent evidence. The first line of evidence is our fundamental understanding of how certain gases trap heat (these so-called GHGs include H_2O, CO_2, CH_4, N_2O, and some other gases and particles that can all absorb the infrared radiation emitted from Earth that otherwise would go to space), how the feedbacks within the climate system respond to increases in these gases, and how other human and natural factors influence climate.

Evidence also comes from using climate models to simulate the climate of the past century, separating the human and natural factors that influence climate. As shown in Figure G-10, when the human factors are removed, these models show that solar and volcanic activity would have tended to slightly cool Earth, and other natural variations are too small to explain the amount of warming. The range of values accounted for the range of results from the different models from around the world that were used in these analyses for the international climate assessment (IPCC 2013). Only when the human influences are included do the models reproduce the warming

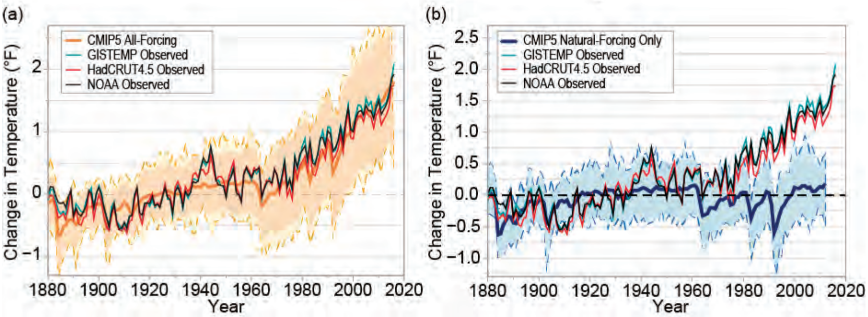


FIGURE G-10 Comparison of observed global mean temperature anomalies from three observational data sets to CMIP5 climate model historical experiments using (a) anthropogenic and natural forcings combined or (b) natural forcings only.
NOTES: In (a) the thick orange curve is the CMIP5 grand ensemble mean across 36 models while the orange shading and outer dashed lines depict the ±2 standard deviations and absolute ranges of annual anomalies across all individual simulations of the 36 models. Model data are a masked blend of surface air temperature over land regions and sea surface temperature over ice-free ocean regions to be more consistent with observations than using surface air temperature alone. All time series (°F) are referenced to a 1901–1960 baseline value. The simulations in (a) have been extended from 2006 through 2016 using the RCP8.5 scenario projections. (b) As in (a), but the blue curves and shading are based on 18 CMIP5 models using natural forcings only. See legends to identify observational data sets. Observations after about 1980 are shown to be inconsistent with the natural forcing-only models (indicating detectable warming) and also consistent with the models that include both anthropogenic and natural forcing, implying that the warming is attributable in part to anthropogenic forcing according to the models.
SOURCE: Adapted from Knutson et al. 2016.

observed over the past 50 years. Over the past five decades, natural drivers of climate such as solar forcing and volcanoes would actually have led to a slight cooling. Accurate observations of the Sun from satellites show that the solar output has actually decreased slightly since 1978 (IPCC 2013).

In another type of analysis, attribution assessment results for different forcings on climate for global mean temperature for the period 1951–2010 from IPCC (2013) are summarized in Figure G-11, which shows assessed *likely* ranges and midpoint estimates for several factors contributing to increases in global mean temperature. The majority of the observed warming can only be explained by the combined effects of the anthropogenic forcing of the warming influence from GHGs and the net cooling influence from particles. Many other studies of past trends in temperature have come to similar conclusions (e.g., Gillett et al. 2012; Santer et al. 2013; Stott et al. 2010).

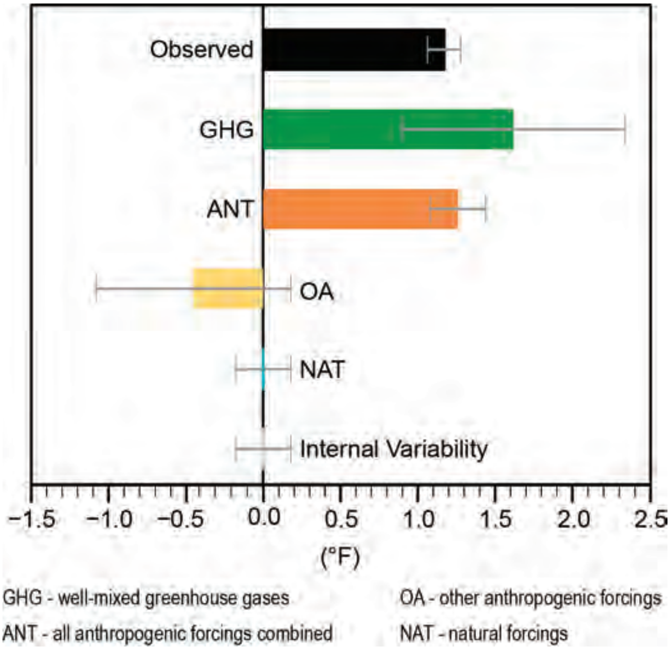


FIGURE G-11 Observed global mean temperature trend (black bar) and attributable warming or cooling influences of anthropogenic and natural forcings over 1951–2010.
NOTES: Observations are from HadCRUT4, along with observational uncertainty (5 percent to 95 percent) error bars (Morice et al. 2012). Likely ranges (bar-whisker plots) and midpoint values (colored bars) for attributable forcings are from IPCC AR5 (Bindoff et al. 2013). GHG refers to well-mixed greenhouse gases, OA to other anthropogenic forcings, NAT to natural forcings, and ANT to all anthropogenic forcings combined. Likely ranges are broader for contributions from well-mixed GHGs and for other anthropogenic forcings, assessed separately, than for the contributions from all anthropogenic forcings combined, because it is more difficult to quantitatively constrain the separate contributions of the various anthropogenic forcing agents.
SOURCE: Redrawn from Bindoff et al. 2013 (used with permission).

Another line of evidence is from reconstructions of past climates using evidence such as tree rings, ice cores, and corals. These show that the change in global surface temperatures over the past five decades are clearly unusual and outside the range of natural variability. These analyses show that the past decade (2000–2009) was warmer than any time in at least the past 1,300 years and perhaps much longer (IPCC 2013; Mann et al. 2008; PAGES 2K Consortium 2013). Through 2016, it appears that this decade will be much warmer than the previous decade.

PROJECTIONS OF FUTURE CHANGES IN CLIMATE

Choices made now and in the next few decades about emissions from fossil fuel use and land use change will determine the amount of additional future warming over this century and beyond. Global emissions of CO_2 and other heat-trapping gases continue to rise. How much climate will change over this century and beyond depends primarily on two factors: (1) human activities and resulting emissions and (2) the sensitivity of the climate to those changes (i.e., the effects of the feedbacks on climate, discussed earlier).

Uncertainties in how the economy will evolve, what types of energy will be used, or what our cities, buildings, or cars will look like in the future are all important and limit the ability to project future changes in climate. Scientists can, however, develop scenarios—plausible projections of what might happen under a given set of assumptions. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of CO_2, and/or global temperature change. The most recent set of time-dependent scenarios, called representative concentration pathways (RCPs) (Moss et al. 2010), are based on a given radiative forcing from which emissions are then evaluated (thus they fit well with prior emission-based scenarios); each scenario is tied to one value, the change in radiative forcing at the tropopause by 2100 relative to preindustrial levels. The four RCPs are numbered according to the change in radiative forcing by 2100: +2.6, +4.5, +6.0, and +8.5 watts per square meter (W/m^2) (Masui et al. 2011; Riahi et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011). The three lower RCP scenarios (2.6, 4.5, and 6.0) are climate policy scenarios, in which future emissions are based on societal decisions to move away from the use of fossil fuels at different rates. At the higher end of the range, the RCP 8.5 scenario corresponds to a future in which carbon and methane emissions continue to rise as a result of fossil fuel use, albeit with significant declines in emission growth rates over the second half of the century. RCP 8.5 reflects the upper range of the open literature on emissions, but is not intended to serve as an upper limit on possible emissions. Note that the RCP 2.6 scenario is much lower than the other scenarios examined because it not only assumes significant mitigation to reduce emissions, but it also assumes that technologies are developed that can achieve net negative CO_2 emissions (removal of CO_2 from the atmosphere) before the end of the century.

A certain amount of climate change is inevitable due to the buildup of CO_2 and other GHGs in the atmosphere (although there is a rapid exchange of CO_2 with the biosphere, the eventual lifetime for atmospheric CO_2 is dependent on removal to the deep ocean). Earth's climate system, particularly the oceans, tends to lag behind changes in atmospheric composition by decades, and even centuries, due to the large heat capacity of the oceans and other factors. Another ~0.5°F (0.2°–0.3°C) increase is expected over the next few decades (Matthews and Zickfeld 2012), although natural variability could still play an important role over this time period (Hawkins and Sutton 2011). The higher the human-related emissions of CO_2 and other heat-trapping gases over the coming decades, the higher the resulting changes expected by midcentury and beyond. By the second half of the century, however, scenario uncertainty (i.e., uncertainty about what will be the level of emissions from human activities) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects (Hawkins and Sutton 2009, 2011).

On the global scale, climate model simulations show consistent projections of future conditions under a range of emission scenarios that depend on assumptions of population change, economic development, our continued use of fossil fuels, changes in other human activities, and other factors. For temperature, all models show warming by late this century that is much larger than historical variations nearly everywhere. Figure G-12 shows the projected changes in globally averaged temperature for a range of future pathways that vary from assuming strong continued dependence on fossil fuels in energy and transportation systems over the 21st century (the high scenario is RCP 8.5) to assuming major emission-reduction actions (the very low scenario, RCP 2.6). Globally and annually averaged temperature changes as large as 6°–10°F (3.3°–5.5°C) are possible by the end of the century if we continue the current pathway of extensively relying on fossil fuels. This would be a very large change relative to past human history (the last ice age was about 12°F (7°C) colder than now). These analyses also suggest that global surface temperature increases for the end of the 21st century are *very likely* to exceed 2.7°F (1.5°C) relative to the 1850–1900 average for all projections, except for the very lowest part of the uncertainty range for RCP 2.6 (IPCC 2013).

Average annual temperature over the contiguous United States is also projected to rise (see Figure G-13). Increases of about 2.5°F (1.4°C) are predicted for the next few decades (i.e., by roughly 2030) in all emission scenarios, implying recent record-setting years may be common in the near future. Much larger rises are projected by late century: 2.8°–7.3°F (1.6°–4.1°C) in a lower-emissions scenario (RCP 4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a higher-emissions scenario (RCP 8.5).

Projections of future changes in precipitation show small increases in the global average but substantial shifts in where and how precipitation falls. Models show decreases in precipitation in the subtropics and increases in precipitation at higher latitudes. Generally, areas closest to the poles are projected to receive more precipitation, while the dry subtropics (the region just outside the tropics, between 23° and 35° on either side of the equator) will generally expand toward the poles and receives less rain.

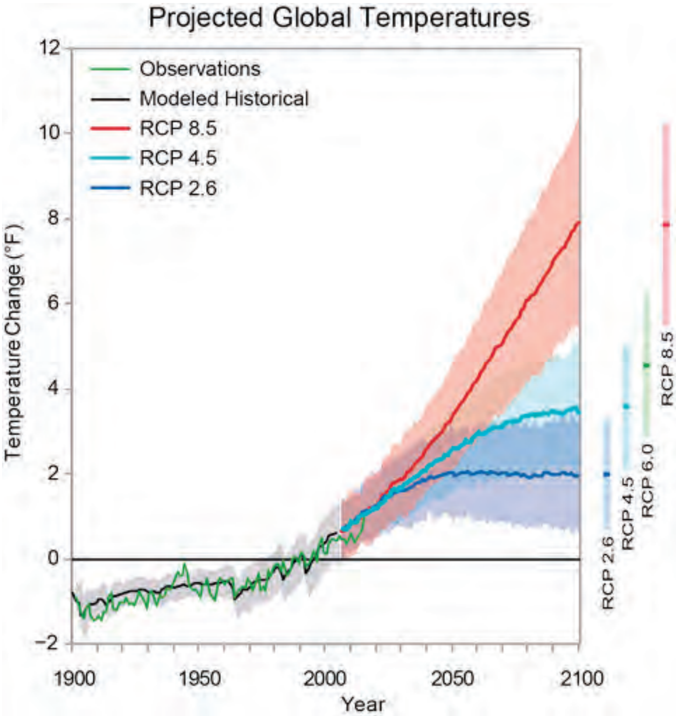


FIGURE G-12 Multimodel simulated time series from 1900 to 2100 for the change in global annual mean surface temperature relative to 1976–2005 for a range of the representative concentration pathway (RCP) scenarios.
NOTES: These scenarios account for the uncertainty in future emissions from human activities (IPCC 2013). The mean and associated uncertainties (1.64 standard deviations [5–95 percent] across the distribution of individual models [shading]) based on the average over 2081–2100 are given for all of the RCP scenarios as colored vertical bars.
SOURCE: Adapted from Walsh et al. 2014.

Increases in tropical precipitation are projected during rainy seasons (such as monsoons), especially over the tropical Pacific. Extreme weather events associated with extremes in temperature and precipitation are likely to continue and to intensify.

For the United States, future changes in seasonal average precipitation will include a mix of increases, decreases, or little change, depending on location and season (see Figure G-14). High-latitude regions are generally projected to become wetter while the subtropical zone is projected to become drier. Because the contiguous United States lies between these two regions, there is significant uncertainty about the sign and magnitude of future anthropogenic changes to seasonal precipitation in much of the region,

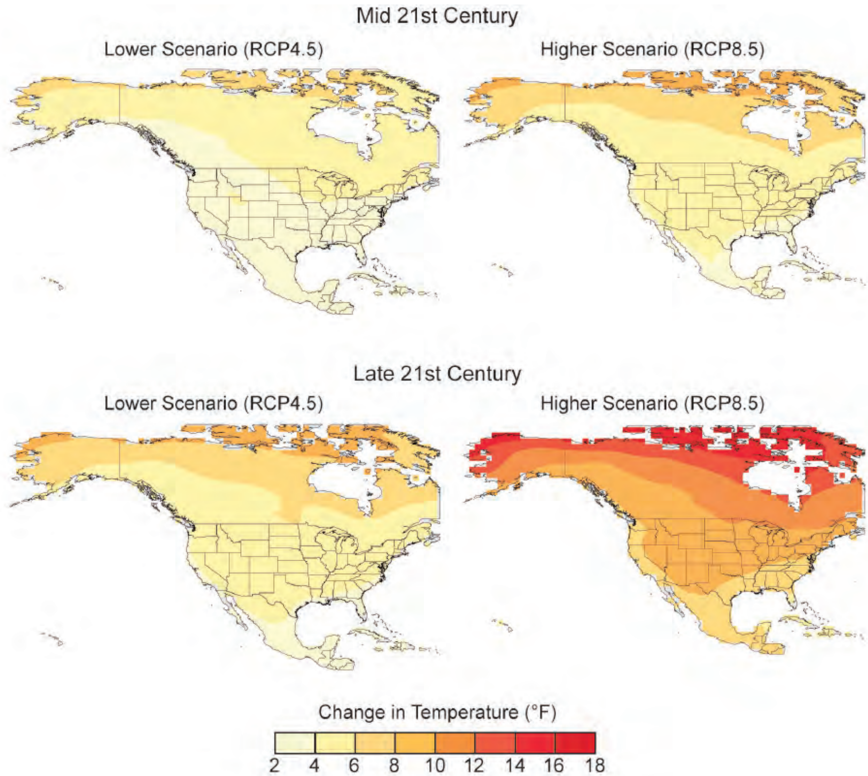


FIGURE G-13 Projected changes in average annual temperature for North America.
NOTES: Changes are the difference between the average for midcentury (2036–2065, top) or late century (2071–2100, bottom) and the average for near present (1976–2005). Each map depicts the weighted multimodel mean. Increases are statistically significant in all areas (i.e., more than 50 percent of the models show a statistically significant change, and more than 67 percent agree on the sign of the change; Sun et al. 2015).
SOURCES: Cooperative Institute for Climate and Satellites and National Oceanic and Atmospheric Administration National Centers for Environmental Information.

particularly in the middle latitudes. Certain regions, including the western United States (especially the Southwest; Melillo et al. 2014), are presently dry and are expected to become drier. The patterns of the projected changes of precipitation do not contain the spatial details that characterize observed precipitation, especially in mountainous terrain, because of model uncertainties and their current spatial resolution (IPCC 2013). Projections indicate large declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States.

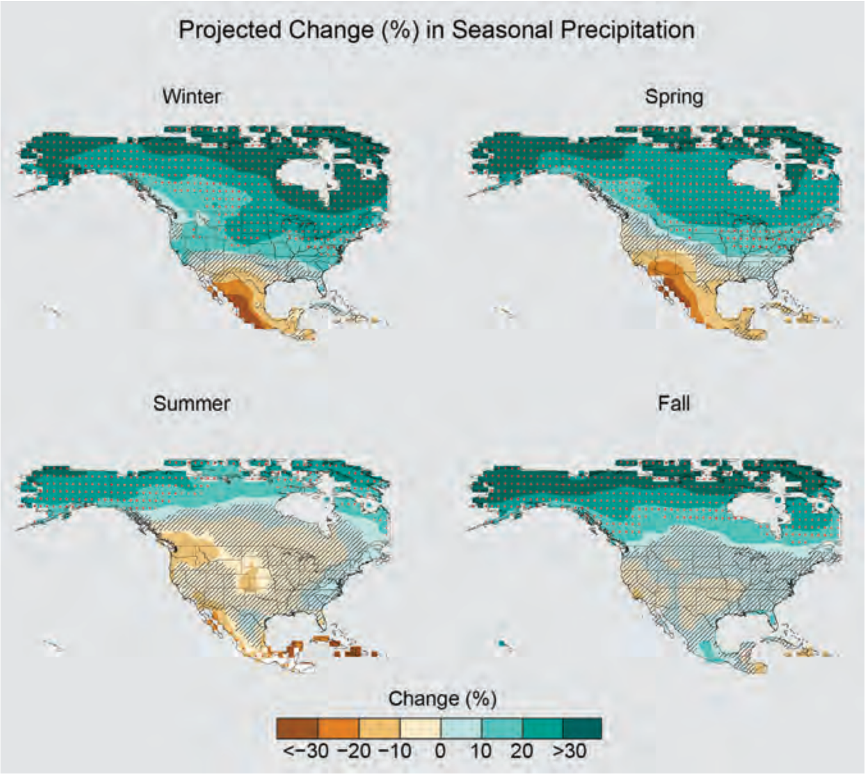


FIGURE G-14 Projected change in total seasonal precipitation from CMIP5 simulations for 2070–2099.
NOTES: The values are weighted multimodel means and expressed as the percentage change relative to the 1976–2005 average. These are results for the RCP 8.5 pathway. Stippling indicates that changes are assessed to be large compared to natural variations. Hatching indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive.
SOURCES: Data from World Climate Research Program (WCRP) Coupled Model Intercomparison Project; figure from National Oceanic and Atmospheric Administration National Centers for Environmental Information.

A number of research studies have examined the potential criteria for dangerous human interferences in climate for which it will be difficult to adapt to the changes in climate without major effects on our society (e.g., Hansen et al. 2016; Kopp et al. 2016). Most of these studies have concluded that an increase in global average temperature of roughly 2.7°F (1.5°C) is an approximate threshold for dangerous human interferences with the climate system (see IPCC [2013, 2014] for further discussion; earlier studies had proposed 2°C), but that this threshold is not exact and the changes in climate are geographically diverse and impacts are sector dependent, and so there really is no defined threshold at which dangerous interferences are actually reached.

The warming and other changes in the climate system will continue beyond 2100 under all RCP scenarios, except for a leveling of temperature under RCP 2.6. In addition, it is fully expected that the warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

PROJECTIONS FOR SEVERE WEATHER, SEA LEVEL, AND LAND SURFACE EFFECTS

The observed trends for extreme weather events related to climate change are likely to continue and further amplify throughout this century and perhaps beyond (depending on the actions we take). Existing research indicates the following trends over the coming decades (see Melillo et al. [2014] or IPCC [2013] for more details):

- It is likely that over the coming decades the frequency of warm days and warm nights will increase in most land regions, while the frequency of cold days and cold nights will decrease. As a result, an increasing tendency for heat waves is likely in many regions of the world.
- Some regions are likely to see an increasing tendency for droughts (especially the Southwest and the Southeast) while others are likely to see an increasing tendency for floods (e.g., the Northeast and the Midwest).
- It is likely that the frequency and intensity of heavy precipitation events will increase over land. These changes are primarily driven by increases in atmospheric water vapor content, but also are affected by changes in atmospheric circulation.
- Tropical storm (hurricane)-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.
- Initial studies also suggest that tornadoes are likely to become more intense, but there are conflicting processes that could affect the resulting trends.
- For some types of extreme events, such as windstorms, ice storms, and hailstorms, there is too little understanding currently of how they will be affected by the changes in climate.

Daily extreme temperatures are projected to increase substantially in the contiguous United States, particularly under the high scenario, RCP 8.5. For instance, the coldest and warmest daily temperatures of the year are expected to increase at least 5°F (2.8°C) in most areas by mid-century (Fischer et al. 2013), rising to 10°F (5.5°C) or more by late century (Sillmann et al. 2013). In general, there will be larger increases in the coldest temperatures of the year, especially in the northern half of the nation, whereas the warmest temperatures will exhibit somewhat more uniform changes geographically (see Figure G-15). On a regional basis, annual extremes are consistently projected to rise faster than annual averages. Future changes in very rare

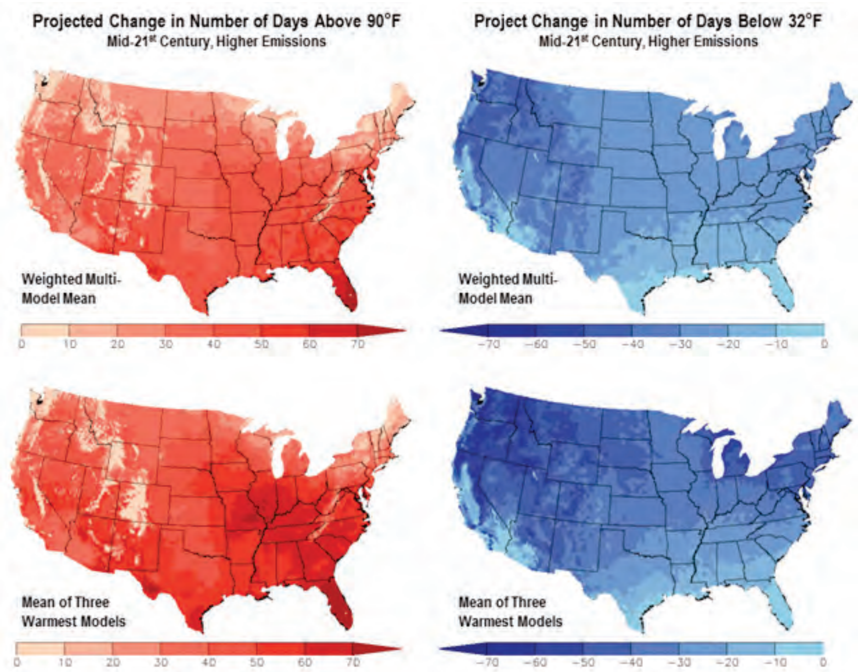


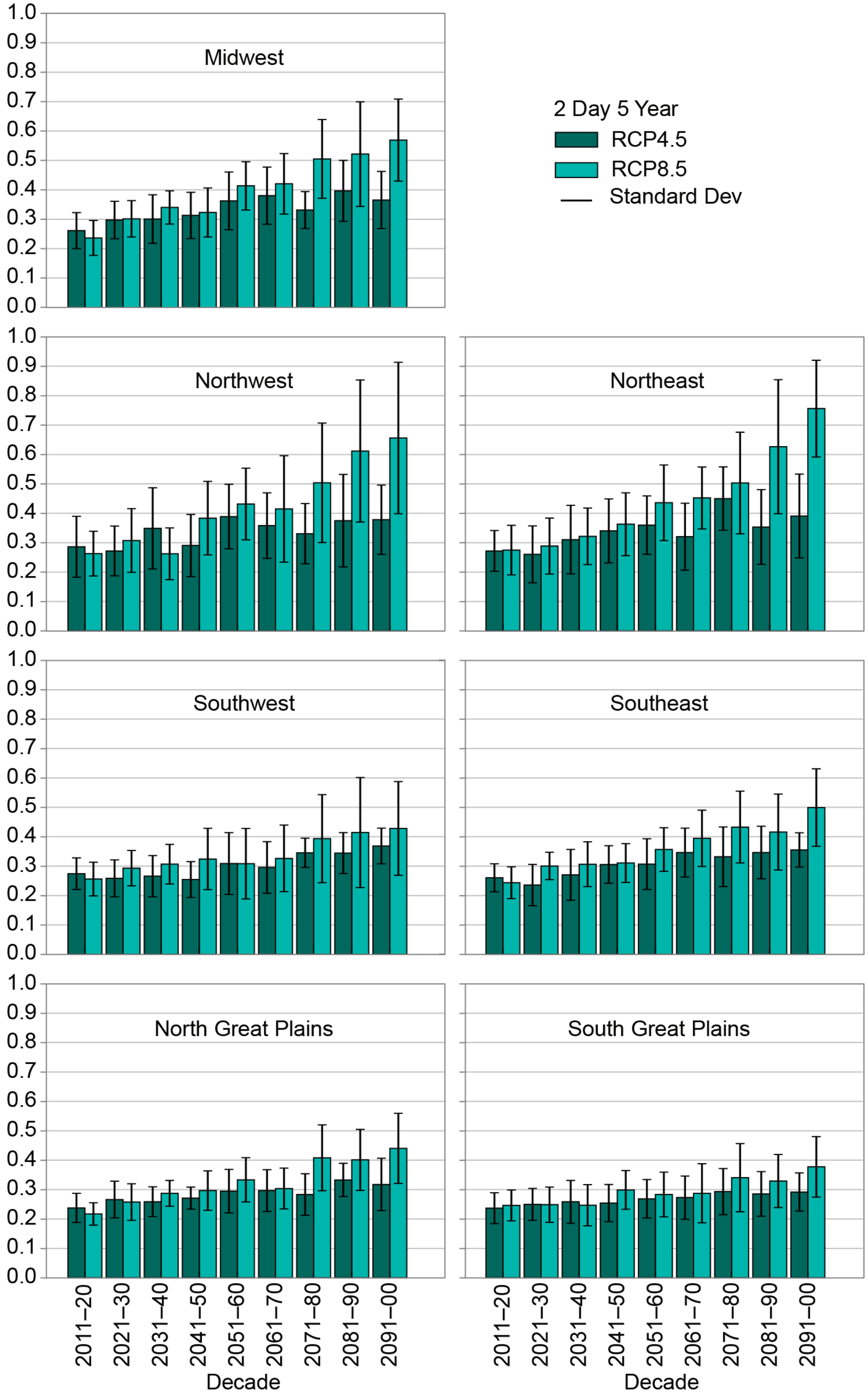
FIGURE G-15 Projected changes in the number of days per year with a maximum temperature above 90°F and a minimum temperature below 32°F in the contiguous United States.
NOTES: Changes are the difference between the average for midcentury (2036–2065) and the average for near present (1976–2005) under RCP 8.5. Maps in the top row depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the three warmest models (i.e., the models with the largest temperature increase). Maps are derived from 32 climate model projections that were statistically downscaled using the localized constructed analogs technique (Pierce et al. 2014). Changes are statistically significant in all areas (i.e., more than 50 percent of the models show a statistically significant change, and more than 67 percent agree on the sign of the change [Sun et al. 2015]).
SOURCES: Cooperative Institute for Climate and Satellites and National Oceanic and Atmospheric Administration National Centers for Environmental Information.

extremes are also striking; by late century, current 1-in-20-year maximums are predicted to occur every year, while current 1-in-20-year minimums are not expected to occur at all (Wuebbles et al. 2014b).

The frequency and intensity of cold waves is projected to decrease while the frequency and intensity of heat waves is projected to increase throughout the century. The frequency of cold waves (6-day periods with a minimum temperature below the 10th percentile) will decrease the most in Alaska and the least in the Northeast, while the frequency of heat waves (6-day periods with a maximum temperature above the 90th percentile) will increase in all regions, particularly the Southeast, Southwest, and Alaska. By midcentury, decreases in the frequency of cold waves are similar across RCPs, whereas increases in the frequency of heat waves are about 50 percent greater in RCP 8.5 than RCP 4.5 (Sun et al. 2015). The intensity of cold waves is projected to decrease while the intensity of heat waves is projected to increase, dramatically so under RCP 8.5. By midcentury, both extreme cold waves and extreme heat waves (e.g., 5-day, 1-in-10-year events) are projected to have temperature increases of at least 11.0°F (6.1°C) nationwide, with larger increases in northern regions (the Northeast, Midwest, Northern Great Plains, and Northwest).

There are large projected changes in the number of days exceeding key temperature thresholds throughout the contiguous United States. For instance, there are about 20 to 30 more days per year with a maximum more than 90°F (32°C) in most areas by midcentury under RCP 8.5, with increases of 40–50 days in much of the Southeast. Consistent with widespread warming, there are 20–30 fewer days per year with a minimum temperature below freezing in the northern and eastern parts of the nation, with decreases of more than 40–50 days in much of the West.

Atmospheric water vapor will increase with increasing temperature, with the result that confidence is *high* that projected future precipitation extremes will increase in frequency and intensity throughout the continental United States. The widespread trend of increasing heavy downpours is expected to continue, with precipitation becoming more intense (e.g., Janssen et al. 2014, 2016; Sillmann et al. 2013). Similar to the observed changes, increases are expected in all regions, even those regions where total precipitation is projected to decline, such as the southwestern United States. Under the RCP 8.5 scenario the number of extreme events (exceeding a 5-year return period) increases by two to three times the historical average in every region (see Figure G-16) by the end of the 21st century, with the largest increases in the Northeast. Under the RCP 4.5 scenario, increases are 50 to 100 percent. Research shows that there is strong evidence, from both the observed record and modeling studies, that increased water vapor resulting from higher temperatures is the primary cause of the increases (Kunkel et al. 2013a, 2013b; Wehner 2013). Additional effects on extreme precipitation


Midwest
Northwest
Northeast
Southwest
Southeast
North Great Plains
South Great Plains
2 Day 5 Year
RCP4.5
RCP8.5
Standard Dev
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2011–20
2021–30
2031–40
2041–50
2051–60
2061–70
2071–80
2081–90
2091–00
Decade

due to changes in dynamical processes are poorly understood. However, projected changes in atmospheric rivers, a narrow corridor of concentrated atmospheric moisture, have been found to increase in number and water vapor transport (Dettinger 2011), as well as resulting in more landfalling at lower latitudes (Shields and Kiehl 2016) as the climate changes—these events can result in significant rainfall on the West Coast.

Around the world, many millions of people and many assets related to energy, transportation, commerce, and ecosystems are located in areas at risk of coastal flooding because of sea level rise and storm surge. Future projections show that by 2100, global mean sea level is *very likely* to rise by 1.6 to 4.3 feet (0.5 to 1.3 meters) under RCP 8.5, 1.1 to 3.1 feet (0.35 to 0.95 meters) under RCP 4.5, and 0.8 to 2.6 feet (0.24 to 0.79 meters) under RCP 2.6 (Kopp et al. 2014 [see Figure G-17]). Recent projections show that for even the lowest-emission scenarios, thermal expansion of ocean waters (Yin and Goddard 2013) and the melting of small mountain glaciers (Marzeion et al. 2012) will result in 11 inches of sea level rise by 2100, even without any contribution from the ice sheets in Greenland and Antarctica. This suggests that about 1 foot (0.3 meters) of global sea level rise by 2100 is probably a realistic low end. Recent analyses suggest that 4 feet (1.2 meters) may be a reasonable upper limit (IPCC 2013; Melillo et al. 2014; Rahmstorf et al. 2012). Although scientists cannot yet assign likelihood to any particular scenario, in general, higher emission scenarios would be expected to lead to higher amounts of sea level rise.

The best estimates for the range of sea level rise projections for this century remain quite large; this may be due in part to what emission scenario we follow, but more importantly it depends on just how much melting occurs from the ice on large land masses, especially from Greenland and Antarctica. Emerging science suggests that the projections may be underestimates, particularly for higher scenarios; a global mean sea level rise

FIGURE G-16 (*Facing Page*) **Regional extreme precipitation event frequency across the contiguous United States for RCP 4.5 (green) and RCP 8.5 (blue) for a 2-day duration and 5-year return.**
NOTES: Regions are based on those being used for the Third National Climate Assessment except that the Great Plains are split into a Northern and a Southern Great Plains (Janssen et al. 2014). Frequency is calculated for 2006–2100 but decadal anomalies begin in 2011. Error bars are ±1 standard deviation; standard deviation is calculated from the 14 or 16 model values that represent the aggregated average over the regions, over the decades, and over the ensemble members of each model. The average frequency for the historical reference period is 0.2 by definition and the values in this graph should be interpreted with respect to a comparison with this historical average value.
SOURCE: Janssen et al. 2014.

exceeding 8 feet (2.4 meters) by 2100 cannot be excluded, and even higher amounts are possible as a result of ice sheet instability.

The U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force (henceforth referred to as Interagency Task Force) (Sweet et al. 2017) recently revised the GMSL rise scenarios for the United States, and now provides six scenarios that can be used for assessment and risk-framing purposes (also shown in Figure G-17). The low scenario of about 1-foot GMSL rise by 2100 is consistent with a continuation of the recent approximately 0.12 inches/year (3 millimeters/year) rate of rise through to 2100, while the five other scenarios span a range of GMSL rise between 1.6 and 8.2 feet (50 and 250 centimeters) in 2100 with corresponding rise rates between 0.2 inches/year (5 millimeters/year) to 1.7 inches/year (44 millimeters/year) toward the end of this century. The highest scenario of 250 centimeters is consistent with several literature estimates of the maximum physically plausible level of 21st century sea level rise (e.g., Pfeffer et al. [2008], updated with Sriver et al. [2012] estimates of thermal expansion, Bamber and Aspinall [2013] estimates of Antarctic contribution, and incorporating land water storage, as discussed in Miller et al. [2013];

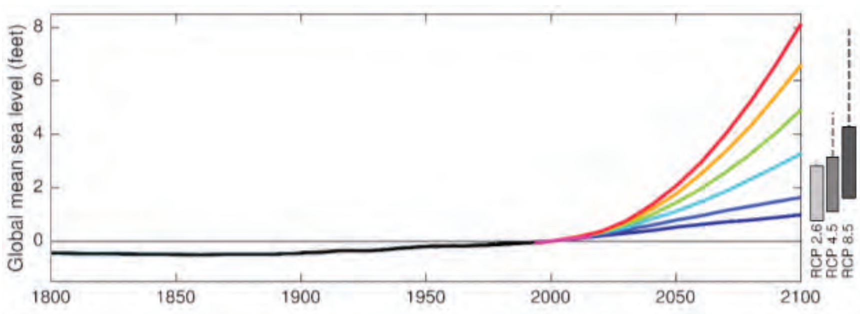


FIGURE G-17 Past and projected mean sea level for six future scenarios.
NOTES: The six Interagency Task Force global mean sea level (GMSL) scenarios of Sweet et al. (2017) are shown over the 2000 to 2100 period relative to historic GMSL estimated by geological, tide gauge, and satellite altimeter reconstructions over 1800 to 2015 (black and magenta lines). The gray-shaded boxes are the central 90 percent conditional probability ranges of representative concentration pathways (RCPs)-based GMSL projections from several recent studies, which are augmented (dashed lines) by the difference between the median Antarctic contribution of Kopp et al. (2014) probabilistic sea level study and the median Antarctic projections of DeConto and Pollard (2016). The scenarios do not necessarily align with any particular RCP-based GMSL solution; rather they span a range of future GMSL rise possibilities. Under the Kopp et al. (2014) framework, which was the basis for the scenario construction, the six scenarios align with a range of probabilistic RCP-based outcomes (e.g., the scenarios span the 2–99.95 percent range for RCP 4.5).
SOURCE: Adaptation of Figure 8 in Sweet et al. 2017.

Kopp et al. [2014]). It is also consistent with the high end of recent projections of Antarctic ice sheet melt (e.g., DeConto and Pollard 2016).

Because of the warmer global temperatures, sea level rise will continue beyond this century. Sea levels will likely continue to rise for many centuries at rates equal to or higher than that of the current century. Many millions of people live within areas than can be affected by the effects of storm surge within a rising sea level. The Low Elevation Coastal Zone (less than 10-meter elevation) constitutes 2 percent of the world's land area, yet contains 10 percent of the world's population (more than 600 million people) (McGranahan et al. 2007; Neumann et al. 2015). Most of the world's megacities are within the coastal zone. By 2030, with sea level rise, the area will expand and 800 million to 900 million people will be exposed (Güneralp et al. 2015; Neumann et al. 2015).

Sea level will not rise uniformly around the coasts of the United States and its overseas territories. Local sea level rise is *likely* to be greater than the global average along the U.S. Atlantic and Gulf Coasts and less than the global average in most of the Pacific Northwest (Sweet et al. 2017). Based on the process-level projections of the Interagency Task Force GMSL scenarios, several key regional patterns are apparent in future U.S. regional sea level (RSL) rise as shown for the intermediate (3.3 feet [1 meter] GMSL rise by 2100) scenario in Figure G-18.

- RSL rise due to Antarctic Ice Sheet melt is greater than GMSL rise along all U.S. coastlines due to static-equilibrium effects.
- RSL rise due to Greenland Ice Sheet melt is less than GMSL rise in the continental United States due to static-equilibrium effects. This effect is especially strong in the Northeast.
- RSL rise is additionally augmented in the Northeast by the effects of glacial isostatic adjustment.
- The Northeast is also exposed to rise due to changes in the Gulf Stream and reductions in the Atlantic meridional overturning circulation (AMOC).
- The western Gulf of Mexico and parts of the U.S. Atlantic Coast south of New York are currently experiencing significant RSL rise caused by the withdrawal of groundwater (along the Atlantic Coast) and of both fossil fuels and groundwater (along the Gulf Coast). Continuation of these practices will further amplify RSL rise.
- The presence of glaciers in Alaska and their proximity to the Pacific Northwest reduces RSL rise in these regions, due to both the ongoing glacial isostatic adjustment to past glacier shrinkage and to the static-equilibrium effects of projected future losses.

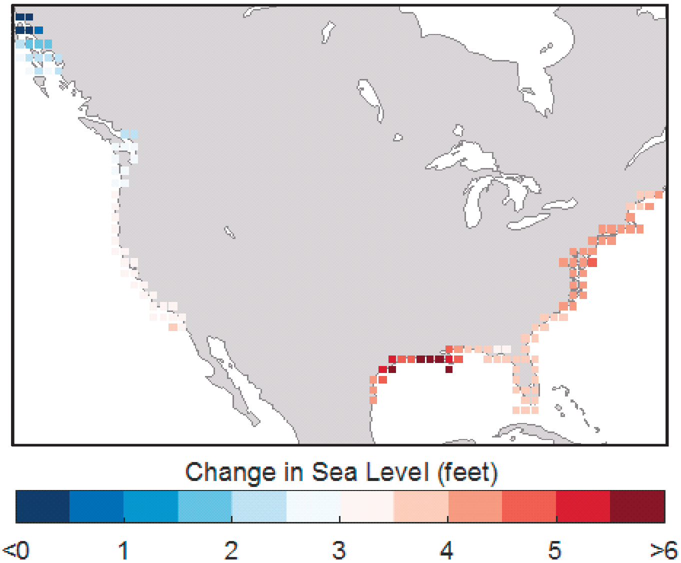


FIGURE G-18 Regional sea level rise in 2100 for the United States projected for the Interagency Task Force Intermediate Scenario (3.3 feet [1-meters] GMSL rise by 2100).
NOTE: Much of the eastern and southern United States are projected to have higher sea level rise than the global average.
SOURCE: Figure adopted from Sweet et al. 2017; based on Figure 12.4b in US-GCRP 2017.

Global sea level rise and its regional variability forced by climatic and ocean circulation patterns are contributing to significant increases in annual tidal-flood frequencies, which are measured by NOAA tide gauges. As seen in Figure G-19, some portions of the U.S. coast (including more than 25 East Coast and Gulf Coast cities) are seeing an accelerating frequency of the impacts from such events (Ezer and Atkinson 2014; Sweet and Park 2014). Trends in annual frequencies surpassing local emergency preparedness thresholds for minor tidal flooding (i.e., "nuisance" levels of about 1 to 2 feet [30 to 60 centimeters]) that begin to flood infrastructure and trigger coastal flood advisories by NOAA's National Weather Service have increased 5- to 10-fold or more since the 1960s along the U.S. coastlines (Sweet et al. 2014). With rising sea levels, such flooding is expected to increase dramatically in the coming decades. The combination of a storm surge at high tide with additional dynamic effects from waves (Stockdon et al. 2006; Sweet et al. 2015) creates the most damaging coastal hydraulic conditions (Moritz et al. 2015).

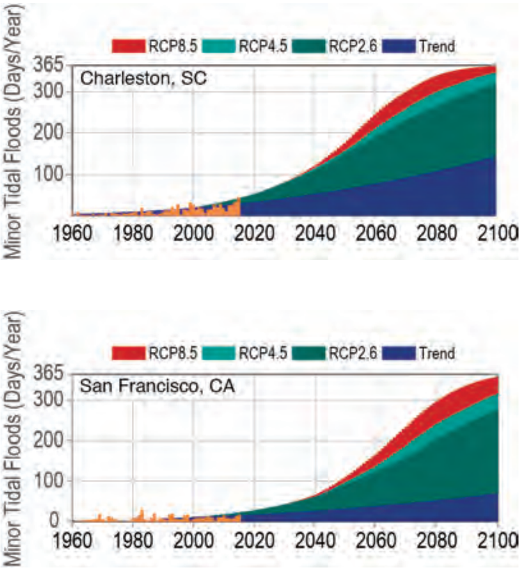


FIGURE G-19 Annual occurrences of daily tidal flooding, also called sunny-day or nuisance flooding, have increased for a number of U.S. coastal cities.
NOTES: Historical exceedances (yellow bars) are shown for two of the locations—Charleston, South Carolina, and San Francisco, California—and future projections through 2100 of the current trend (blue) and under median RCP 2.6 (green), 4.5 (teal), and 8.5 (red) conditions.
SOURCE: Based on Sweet and Park 2014.

Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more discontinuous. Alaskan and Arctic permafrost characteristics have responded to increased temperatures and reduced snow cover in most regions since the 1980s (AMAP 2011). The permafrost warming rate varies regionally; however, colder permafrost is warming faster than warmer permafrost (Romanovsky et al. 2015; Vaughan et al. 2013). This feature is most evident across Alaska, where permafrost on the North Slope is warming more rapidly than in the interior. This results in significant potential effects on buildings and roads in that region.

OVERVIEW OF ENVIRONMENTAL VARIABLES AND EXTREME EVENTS AND THE INTERSTATE HIGHWAY SYSTEM

Climate variability and change affect U.S. DOT's strategic goals of safety, state of good repair, and environmental sustainability for all transportation modes including the U.S. Interstate Highway System (FHWA n.d.; U.S.

DOT 2014). For the Interstate System, climate variability and change may accelerate asset deterioration, increase operational disruptions, or cause catastrophic failure of structures. In some cases, such as projected winter weather moderation, climate change may positively affect the Interstate System. Notable impacts identified by U.S. DOT are wide-ranging and not limited to the Interstate Highway System (see Figure G-20). Some impacts may require changes in the planning, design, construction, and/or maintenance of infrastructure. At a national level, addressing potential climate impacts in planning and project development is one priority that will allow transportation systems to gradually become resilient to the future climate (U.S. DOT 2014). Another priority is incorporating climate change as a risk in risk-based asset management to allow assessment of climate risk consistently with the other risks that impact assets.

Traditionally, infrastructure design standards and guidelines have used historical weather and climate observations to determine the environmental stress that an asset should be designed to withstand over its service life. However, in a nonstationary climate, past weather is not a reliable indicator of future weather and may not be appropriate for infrastructure design. The current trends for average climate and extreme weather events are likely to continue and further amplify throughout this century. Most Interstate System assets are designed to remain in service for decades or even longer. The decisions made today about future environmental risks will impact the costs, service, and design life of infrastructure assets.

Potential climate impacts to the Interstate Highway System vary greatly depending on the climate stressor, the asset, and its location. Numerous infrastructure impacts are anticipated from projected temperature, precipitation, and sea level rise change (TRB 2014). Strategies to mitigate future impacts include planning, design, and operations/maintenance approaches (Caltrans 2013). Infrastructure impacts and strategies may also differ between existing and new infrastructure. The vulnerability of existing transportation infrastructure to future climate varies greatly due to its age, service life, location, and original design standards. As existing infrastructure ages, decisions about repair, replacement, or abandonment should take into account the future climate. New infrastructure can be designed and built to handle future environmental risks.

New strategies to incorporate future climate in infrastructure planning and design processes are now emerging. In 2014, FHWA released *Hydraulic Engineering Circular 25—Volume 2: Highways in the Coastal Environment: Assessing Extreme Events*. HEC 25 provides technical guidance and methodologies for incorporating climate change considerations, including sea level rise, storm surge, and wave action, into planning and design analyses for highway projects in the coastal environment (Douglass et al. 2014). In 2016, FHWA released *HEC 17—Highways in the River Environment: Floodplains,*

Notable Potential Impacts to the Interstate Highway System

- More frequent/severe flooding of underground tunnels and low-lying infrastructure, requiring drainage and pumping, due to more intense precipitation, sea level rise, and storm surge.
- Increased numbers and magnitude of storm surges and/or relative sea level rise potentially shorten infrastructure life.
- Increased thermal expansion of paved surfaces, potentially causing degradation andreduced service life, due to higher temperatures and increased duration of heat waves.
- Higher maintenance/construction costs for roads and bridges, due to increased temperatures, or exposure to storm surge.
- Asphalt degradation and shorter replacement cycles; leading to limited access, congestion, and higher costs, due to higher temperatures.
- Culvert and drainage infrastructure damage, due to changes in precipitation intensity, or snow melt timing.
- Decreased driver/operator performance and decision-making skills, due to driver fatigue asa result of adverse weather.
- Increased risk of vehicle crashes in severe weather.

Notable Potential Impacts to Alternative Transport Modes

- System downtime, derailments, and slower travel times, due to rail buckling duringextremely hot days.
- Reduced aircraft performance leading to limited range capabilities and reduced payloads.
- Air traffic disruptions, due to severe weather and precipitation events that impact arrival and departure rates.
- Reduced shipping access to docks and shore equipment and navigational aid damage.
- Restricted access to local economies and public transportation.

FIGURE G-20 Notable potential impacts to the Interstate Highway System and other transportation modes.
SOURCE: Adaptation of Figure 1 in U.S. DOT 2014.

Extreme Events, Risk, and Resilience, 2nd ed. (Kilgore et al. 2016). HEC 17 provides technical guidance and methodologies for incorporating climate change considerations, with a focus on extreme flood events, into highway projects' planning and design analyses in the riverine environments.

Transportation systems are interdependent. When climate and weather compromise passenger and freight ability to reach their destination safely and efficiently using the Interstate Highway System, other modes of transportation are simultaneously affected and the overall system performance may be further compromised. However, because impacts on infrastructure and operations differ by mode, redundancies within the Interstate Highway System and other modes may allow the system to function efficiently.

DIRECT EFFECTS OF PROJECTED FUTURE CLIMATE ON THE INTERSTATE HIGHWAY SYSTEM

The Interstate Highway System and Temperature Changes

Warming average temperatures, heat waves, and record-setting summer temperatures have immediate and long-term impacts on the Interstate Highway System. Sustained heat compromises pavement integrity by increasing rutting, cracking, and buckling while stressing bridge decks and joints. Vehicle mechanical failures including tire blowouts and overheating are linked to high temperatures. Elevated temperatures also affect transport capacity, safety, and construction. Under extremely hot temperatures, excessive expansion can cause roadway joints to buckle and, potentially, send vehicles airborne or cause the driver to lose control. Repairing pavement from heat waves and drought in addition to accelerated deterioration from higher average temperatures is already affecting state DOTs' operations and maintenance activities. The Iowa DOT spends $400,000 annually to make temporary and permanent repairs to buckled pavement. Virginia DOT has crews available to quickly repair potholes or buckling pavement during extreme heat events (Gopalakrishna et al. 2013).

For flexible pavements, higher average air temperatures will increase the maximum pavement temperature and the potential for rutting and shoving, particularly during extreme heat waves. For example, by midcentury in the Northeast, projected warming temperatures would increase asphalt concrete rutting 10 to 25 percent and reduce a typical Interstate pavement life span by 1 to 6 years as compared to current condition (see Figure G-21). These changes may be addressed through more rut-resistant asphalt mixtures and/or increased use of rut-resistant designs, but current binder grade selection guidelines may no longer be appropriate. Accelerated age hardening of asphalt binder is also a concern. For rigid pavement, there is an increased potential for concrete temperature-related curling that may require new design strategies. For existing pavements, attention to routine joint maintenance may be adequate to accommodate additional expansion, but in some cases new expansion joints may be required (Muench and Van Dam 2015).

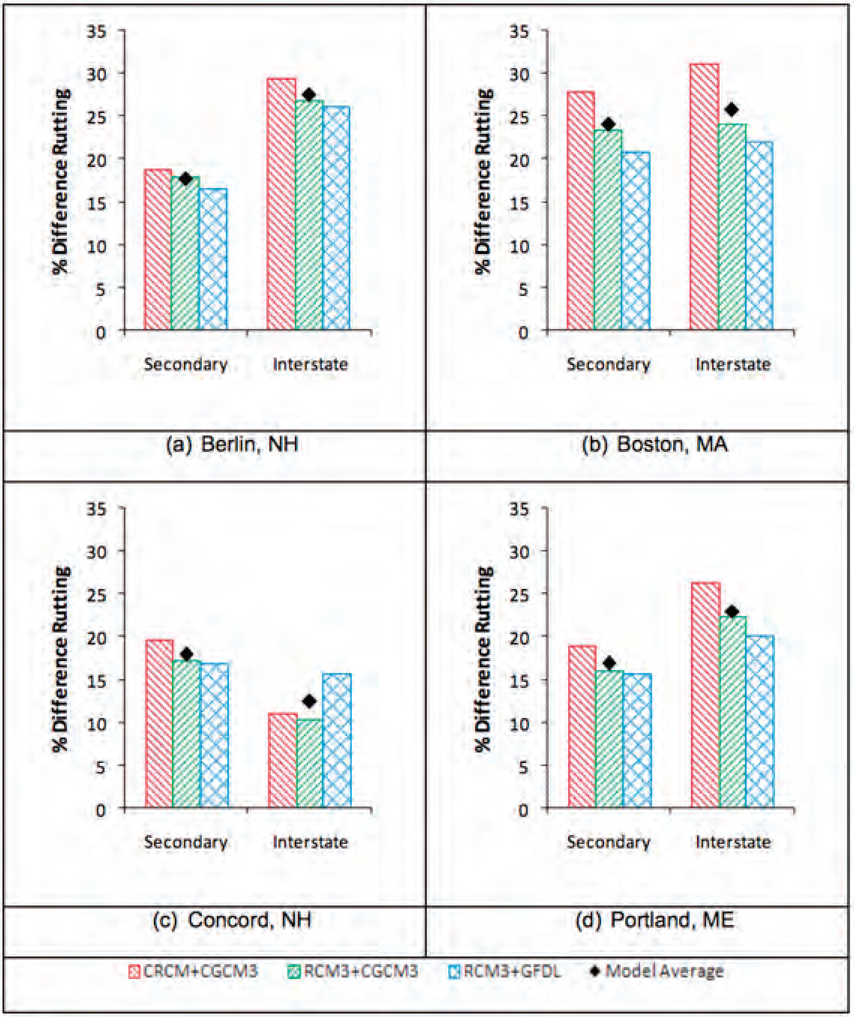


FIGURE G-21 Percentage difference in asphalt concrete rutting between baseline and future periods.

NOTES: Temperature values were obtained from the North American Regional Climate Change Assessment Program's climate change simulations for the baseline period 1971–2000 and for the future period 2041–2070. Rutting was determined using the Mechanistic-Empirical Pavement Design Guide with typical pavement structures representing a secondary road and an Interstate.

SOURCE: Adaptation of Figure 7 in Meagher et al. 2012.

High temperatures and rapid temperature changes can induce differential movement of joint and deck stress materials and may lead to premature failure (Meyer et al. 2013). Most in-service bridges' bearings and expansion joints can accommodate the modest projected additional expansion (see Figure G-22). However, if the bridge joints cannot handle expansion extremes, then large forces could develop that severely affect the bridges (Niemeier et al. 2013; Peterson et al. 2008). In this case, the enhanced risk of structural damage may necessitate mandatory traffic diversion or load restrictions, particularly for freight, to more robust alternative routes (Gopalakrishna et al. 2013).

Construction activities are sensitive to high temperatures. Heat compromises worker and public safety. Higher extreme temperatures affect construction scheduling. Protocols governing worker safety limit construction during heat waves, reduce productivity, or require work to be conducted at night (Anderson et al. 2015b; Baglin 2012; Cambridge Systematics, Inc. 2015). There are also temperature limitations on some construction activities including road painting, asphalt paving, and concrete pouring.

Warming conditions will affect aspects of the Interstate Highway System beyond bridges and pavements. In urban areas, temperature effects in tunnels may be amplified because there is additional heat generated by equipment and vehicles, and tunnels have reduced cooling efficiency. Electrical support equipment, including monitoring equipment, communication lines, and power lines, can be damaged by heat, overheat, or fail during rolling blackouts (Asam et al. 2015). Increased cooling costs for some assets will occur in the summer, but may be offset by decreased heating costs in the winter. Freight using the Interstate Highway System will need increased refrigeration to alleviate cargo overheating (Caltrans 2013; U.S. DOT 2015).

Warming winters with less frequent extremely cold days and extreme cold waves are anticipated to extend the construction season and reduce winter road maintenance demand. In southern regions, fewer snow and icing events will likely reduce vehicle accident risk (Cambridge Systematics, Inc. 2015; Tamerius et al. 2016) as well as decreased transport delays from grounded freight. Warming winters are also anticipated to reduce frost heaves and pavement degradation from freeze–thaw transitions in most regions. However, some locations that historically have had long, hard winters may experience increased road degradation due to more moderate freeze conditions, increased freeze–thaw conditions, and expanded use of deicing agents. For example, historically, Fairbanks, Alaska, and its interior roads would stay frozen from mid-fall to late spring. However, thawing and freezing rain events have now caused the Alaska Department of Transportation & Public Facilities to perform anti-icing (Asam et al. 2015). Damage to bridges and roads caused by potholes and frost heaves cost hundreds of millions of dollars annually (Peterson et al. 2008), and changing winter

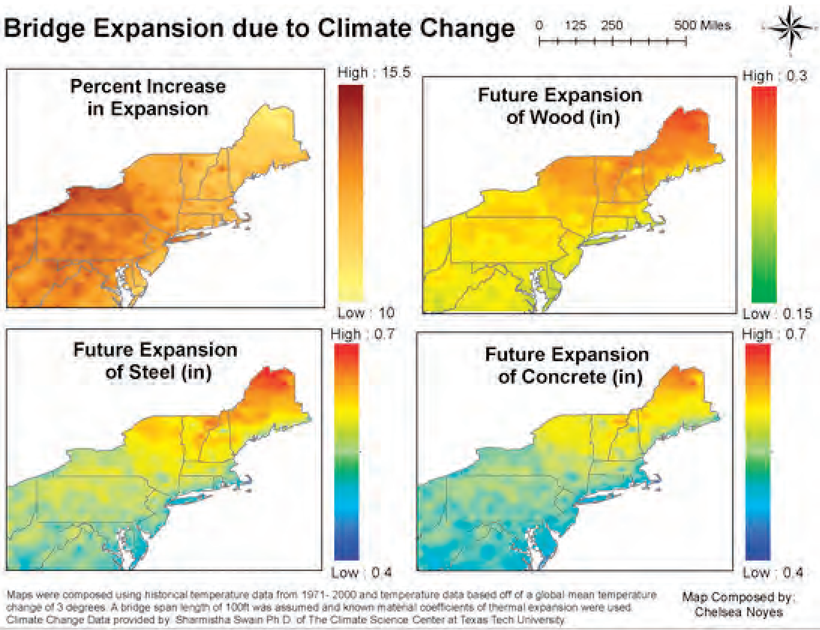


FIGURE G-22 Percentage difference in bridge joint expansion and increase in expansion magnitude for wood, steel, and concrete spans between baseline (1971–2000) and future temperatures in New England.
NOTES: The future New England temperatures reflect those temperatures that occur when global mean temperatures increase by 5.4°F (3°C). It is likely that this warming will not be reached until 2065–2084, but these thresholds could be reached as early as 2050–2069 under a high-emission scenario (http://theicnet.org/?page_id=46).
SOURCE: C. Noyes and J. M. Jacobs, unpublished study, 2015.

conditions will likely alleviate expenditures in some regions and amplify expenditures in other regions. In Alaska, the melting permafrost will have significant impacts on roads, bridges, and culverts and adjacent land due to ground settlement. This ground movement is particularly problematic for bridges and roads and also deforms the road surface (TRB 2014).

The Interstate Highway System and Changes to Precipitation and Intense Rainfall

The Interstate Highway System is highly vulnerable to flood events and mudslides/landslides from long-duration rainfall. From 2014 to 2016, the Dartmouth Flood Observatory reported 30 major floods in the United States. In the first 5 months of 2017, five major flooding and mudslide events shut down the Interstate System for days or weeks including Northern (I-80) and Southern California (I-880) in January, North Central California (I-5) in February, Idaho (I-86) in March, and the Central United States including Missouri (I-44 and I-55) in May.

Changing seasonal precipitation, increased rainfall intensity, and snow and rain transitions will affect the Interstate Highway System in a number of ways. As precipitation increases during winter months and changes from snow to rain due to warming winters, spring river flooding is anticipated to increase. More precipitation may cause groundwater tables to rise, thus increasing soil saturation and affecting the pavement strength of the Interstates, foundation integrity, and tunnel function. The upper Midwest is increasingly vulnerable to spring floods from the changing climate (Hirsch and Ryberg 2012).

The most dramatic impact from increased precipitation extremes is an elevated risk of flooded highways, tunnels, drainage systems, and secondary roads. Flooded pavements are subject to washouts or accelerated deterioration. Intense storms can cause steep embankments to fail, leading to road closures. Severe storms with intense precipitation and high winds can damage signs, overhead cables, and other tall structures and topple trees. Heavier rainfall events and more intense storms also have serious driver safety implications. Crash rates increase by more than 50 percent with heavier rainfall intensities, and annual rainfall totals are linked to higher risk of accidents (Tamerius et al. 2016; Winguth et al. 2016). While all regions may see increased flooding impacts from climate change, the Northeast is particularly at risk from increasingly heavy rainfall while the Pacific Northwest faces increased slope stability challenges.

Flooding and extreme precipitation are among the most studied climate change stressors in recent transportation vulnerability studies. For example, Iowa's transportation infrastructure has repeat-flooded as recently as 2008 and 2016 (see Figure G-23). Multiple studies have found that many of the 4,100 bridges and structures in the state's primary highway system are affected during flooding. The FHWA pilot study of Iowa found that all of the study's Interstate and highway locations would be exposed to streamflow that exceeds current design standards and have increased vulnerability from more frequent episodes of highway overtopping. Additionally, bridges have higher vulnerability to potential bridge scour over the design lifetime of the bridge (Anderson et al. 2015a).

Bridges are highly vulnerable to flooding events. The common bridge failure modes are scour, in which bridge foundations are compromised due to erosion, and failure during single-event floods of record (Flint et al. 2017). Scour failures can result from a series of strong storm events that collectively weaken the foundation. In some regions of the country, more than 75 percent of inland bridges are vulnerable due to climate change (see Figure G-24).

FIGURE G-23 Repeated floods in Iowa, including Cedar Rapids and Iowa City, closed I-80 in 2008 and threatened I-80 and I-380 again in 2016.
SOURCE: U.S. Army Corps of Engineers.

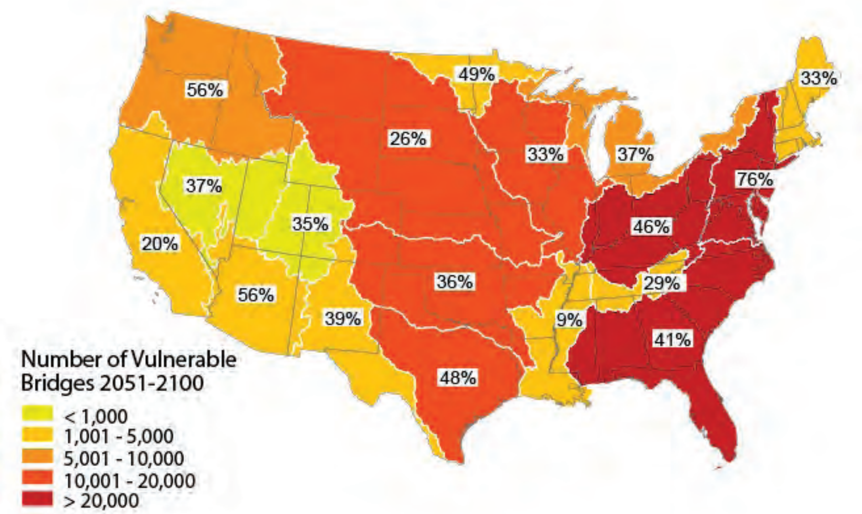


FIGURE G-24 Inland bridges identified as vulnerable in the second half of the 21st century due to climate change.
SOURCE: Adaptation of Figure 1 in EPA 2015, 34.

Pavements are affected by annual precipitation changes as well as extremes. Wetter conditions will reduce the pavement structure load capacity, require improved surface and subsurface drainage, and likely negatively affect construction because of weather-related delays (Muench and Van Dam 2015). The trend to wetter winters and drier summers can amplify soil shrinking and swelling due to moisture changes. Impacts to roads from extreme rainfall include flooding and potential washout that close routes and cause travel delays. Flooding can also contribute to reduced pavement lifetime from decreased structural capacity when the base and subgrades are saturated. Additionally, increasing frequency and magnitude of moderate rainfall events will affect safety if the wet road surfaces do not have adequate friction or visible pavement markings.

Sea Level Rise, Storm Surge, and Nuisance Flooding Changes

The Interstate System's infrastructure in the coastal zones is already vulnerable to coastal extreme events; this vulnerability will increase with sea level rise, enhanced storm surge from tropical and nontropical storms, and land subsidence (Douglass et al. 2014; Peterson et al. 2008). Hurricanes Matthew (2016), Sandy (2012), Ike (2008), and Katrina (2005) caused billions of dollars in damage to coastal roadways and bridges. Significant economic losses also occurred due to transport disruption during and after these storms. During Hurricane Katrina, a 27-foot storm surge in coastal Mississippi washed out roads, bridges, and railways. Currently, 60,000 miles of highway are exposed to coastal storms (see Douglass et al. 2014). In the future, disruptions and damage will occur more frequently, and rising seas will result in more severe events. Rising seas will cause storm surge impacts to extend farther inland and into new parts of the country. Infrastructure in these locations may be more susceptible to damage because they were not built to withstand damaging storm waves (U.S. DOT 2015). Coastal Interstates function as an evacuation route is anticipated to increase (GAO 2013) despite declining performance abilities due to sea level rise. Impacts on the Interstate Highway System during extreme events will delay evacuations and compromise the safety of the public and first responders.

The primary natural processes that affect coastal Interstate infrastructure are coastal water levels, waves, and high-velocity flows. Additional challenges may result from shoreline erosion and deposition, reduced drainage capacity, roadway failures due to elevated groundwater tables, the loss of protective coastal wetlands, and saltwater intrusion and corrosion (Douglass et al. 2014). For bridges, accelerated corrosion will shorten the life expectancy and increase maintenance costs as well as increase the likelihood of structural failure (TRB 2014).

Coastal and inland tidal zone flooding will affect the Interstate Highway System by flooding roadways, damaging pavements, and disrupting transportation. For moderate storm events, rising seas present a flooding risk to low-lying roadways and underground infrastructure, such as road tunnels, during storm events. Culverts that are undersized for new flows may induce flooding in new locations or prolong flooding in existing vulnerable areas. During tropical storms (e.g., Hurricane Sandy), flooded highways and tunnels are prolific. Waves on top of a storm surge promote flooding and can damage coastal bridge super- and substructures. Waves on storm surge in the Gulf Coast hurricanes of 2004–2005 caused billions of dollars in damage to bridges including moving bridge deck spans that weighed more than 340,000 pounds each (see Figure G-25).

Sea level rise will also increase coastal erosion and cause damage to the substructure or a complete washout of vulnerable roadways. Periodic route closures and travel delays will result. Flowing water combined with waves and storm surge will damage embankments and pavements. In the Pacific Northwest, damage to roadways occurs on coastal bluffs due to waves and wave runup that creates erosion; portions of the Pacific Coast Highway have already been relocated due to bluff erosion (Hormann 2012). Erosion also causes scour on critical bridges in coastal zones and may compromise their integrity, leading to reduced capacity or even failure resulting in closure.

The coastal storm impacts on the Interstates from future extreme events depend on a combination of sea level rise, whose magnitude varies by

FIGURE G-25 Lake Pontchartrain Bridge damage from Hurricane Katrina.
SOURCES: Adaptation of Figure 1.3 in Xu 2015, adopted from Sheppard and Marin 2009.

region, regional extreme events, and local conditions. In the Gulf of Mexico and South Atlantic coasts, tropical storms and hurricanes are key extreme events. Storm surge and wave impacts depend on the tide cycle, tropical storm position, wind stress, and inland rainfall-induced flooding. In the mid-Atlantic and New England, the timing and duration of tropical and nontropical storm surges relative to tide cycles are critical because tides range from 2 to 9 feet. On the Pacific Coast and in Alaska, El Niño and tsunamis combine with 6 feet or greater tides that enhance coastal flooding during storms. Additionally, major Pacific storms typically last multiple days, with the greatest impact occur during astronomical high tides.

In some coastal areas, impacts on the Interstates will not be limited to storm events. Routine "sunny day flooding" is already occurring during moderate to extreme high tides. Phase I of the U.S. DOT Gulf Coast Study, completed in 2008, found that with 4 feet of sea level rise, 27 percent of the Gulf Coast region's major highways as well as 9 percent of rail lines and 72 percent of ports would be inundated (FHWA n.d.). Emerging findings on rising groundwater due to sea level rise show that groundwater response occurs two to four times farther inland than surface water inundation, thus blurring the coastal and inland divide (Knott et al. 2018). Groundwater-induced impacts to roads occur where the groundwater is already high, with modest performance reduction for engineered Interstate pavements unless the road becomes inundated. A secondary impact from rising groundwater is wetland expansion that may affect permitting of new projects.

Because sea level rise–induced coastal flooding decreases service and increases maintenance costs for existing facilities, mitigation strategies will be an increasingly critical aspect of transportation planning, design, and operations. Planning activities can identify those portions of the Interstate roadways and bridges that will likely be vulnerable to future flooding and erosion, address the future vulnerability in transportation plans, and, as needed, design redundancy into the system to account for declining performance. Design practices may protect infrastructure from future flooding and storm surges by strengthening and raising infrastructure and developing protective seawalls and drainage. In some cases, Interstate roadways may need to be relocated or abandoned. Damages and repair needs will rise for existing roadways. As weather-related delays become more frequent and expand in extent, operations and maintenance will need to ensure that drainage systems function efficiently. Advanced monitoring, forecasting, and communicating tools can provide system users timely information about route status and alternative routes.

INDIRECT EFFECTS OF PROJECTED FUTURE CLIMATE ON THE INTERSTATE HIGHWAY SYSTEM

The Interstate Highway System and Inland Navigation

Industries that need inland transport services can use barges, trains, or trucks. For the Interstate Highway System, changes in access to or reliability of another mode of transportation may change the shipment mode. If inland navigation via ships and barges is negatively impacted by climate change, then the demand for truck and rail transport may increase. Potential climate change impacts to inland waterways are winter conditions, water levels, and siltation. Winter conditions affect the waterway's shipping season. Water levels and siltation control the number of days per year that waterways can be used without restrictions.

Northern inland ports on the Great Lakes and the Saint Lawrence Seaway are closed and icebound in the winter. Milder winters will lengthen the shipping season on both the Great Lakes and the Seaway (Moser et al. 2008; U.S. DOT 2014). Water levels in the Mississippi and Ohio Rivers, the Saint Lawrence Seaway, and the Great Lakes are sensitive to changes in the long-term water balance driven by precipitation and temperature as well as flooding and drought. Lower water levels restrict some boat access to ports and shipping channels or require shipping companies to lighten loads in order to reduce draft. In recent years, water levels on the Great Lakes and the Seaway have been at historical lows. There is some evidence that climate change will drop the Great Lakes water levels (Angel and Kunkel 2010; Attavanich et al. 2013) and enhance seasonal variability (MacKay and Seglenieks 2013), but results vary among studies and climate models (see Figure G-26). Thus, the certainty about changing water levels is low (U.S. DOT 2014). Similar to water levels, siltation is already a significant challenge in the Great Lakes waters with dredging needed to maintain channel depth. Increased intense storms could lead to more erosion in watersheds and siltation and temporary waterway closures that shift cargo to trucks.

The Interstate Highway System and Disruption from Dust and Fire

Dust storms and smoke from wildfires can lower visibility substantially. Limited visibility in transportation corridors disrupts operations and affects safety. In the Southwest, dust storms and wildfires have forced extended road closures and endangered drivers (Meyer et al. 2013). Projections of drier summer and fall seasons as well as extended heat waves and droughts in the central Contiguous United States could potentially increase blowing dust and wildfires and threaten portions of the Interstate Highway System (FHWA 2016; NRC 2008). Increased summer temperatures are projected

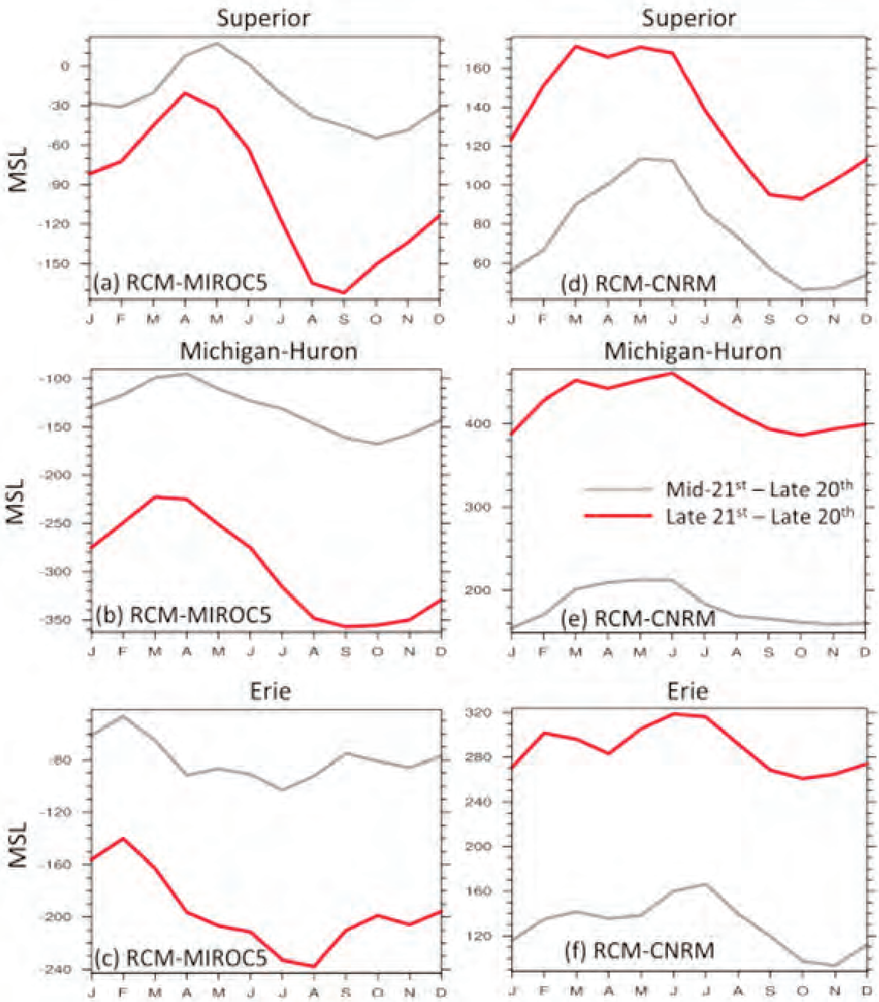


FIGURE G-26 Summary of projected lake level change from mean sea level (MSL) for Lakes Superior, Michigan, and Erie by month.
NOTES: Gray lines are for the mid-21st century (2040–2059) and red lines are for late 21st century (2080–2099) as compared to the late 20th century (1948–2006) using dynamically downscaled model output from two regional climate models (a)–(c) RCM-MIROC5 and (d)–(f) RCM-CNRM.
SOURCE: Adaptation of Figure 13 in Notaro et al. 2015.

to elevate the fire risk up to 30 percent by 2100 (IPCC 2007). In the Pacific Northwest, drier summer conditions, due to warmer temperatures combined with shorter winters, will increase wildfire risk (USGCRP 2009). Wildfires routinely close the Interstate System in Oregon during fires because of proximity of the fire or when the road is used as a staging area for firefighting crews (Hormann 2012). Regional assessments conducted through the FHWA Pilot Program generally found future dust and wildfire trends to be highly uncertain (FHWA 2016). Although these are not new events to many regions, changes in the frequency, duration, and intensity could affect the Interstate System performance (FHWA n.d.; Gopalakrishna et al. 2013).

The Interstate Highway System and Arctic Sea Ice Opening Northern Transportation Routes

Opening of the Arctic sea ice has recently generated significant consideration about the potential for Arctic shipping routes using the Northwest Passage (NWP) to ship goods between Asia and the eastern United States. Arctic shipping lanes offer vessels a shorter route and, for large vehicles that cannot use the Panama Canal, an alternative to shipping goods via rail or highways to the eastern United States (Niemeier et al. 2013). The use of the NWP could reduce cargo delivered to western U.S. ports and associated trucking across the United States (Pharand 2007) and change the distribution of goods between the western and eastern U.S. ports (see Figure G-27). Increasingly, potential shipping lanes that are ice-free exist across the breadth of the Arctic during the summer. Canada's International Policy Statement predicted in 2005 that the NWP would be sufficiently ice-free for regular use during summer as early as 2015 (Government of Canada 2005), but to date dramatic increases in commercial ship traffic remain unrealized.

Under ideal conditions, the economics are somewhat balanced in favor of using the NWP to transport goods from northern Asia to eastern North America and Europe (Kiiski 2017). These conditions would at best result in tens of millions of tons of cargo, two orders of magnitude less than the Suez Canal. However, there are significant barriers to the NWP, including variable weather and ice conditions, the availability of ice breakers and ice-classed ships, and inadequate port infrastructure (Kiiski 2017; Lackenbauer and Lajeunesse 2014; Stephens 2016). Given this balance, Stephens (2016) indicates that the NWP appears unlikely to have a major impact in the near future (20 to 25 years or longer).

The Interstate Highway System and Northward Changes in Agricultural Production

Climate change will likely shift the location of production centers for agriculture, forestry, and fisheries. For agriculture, climate change will increase

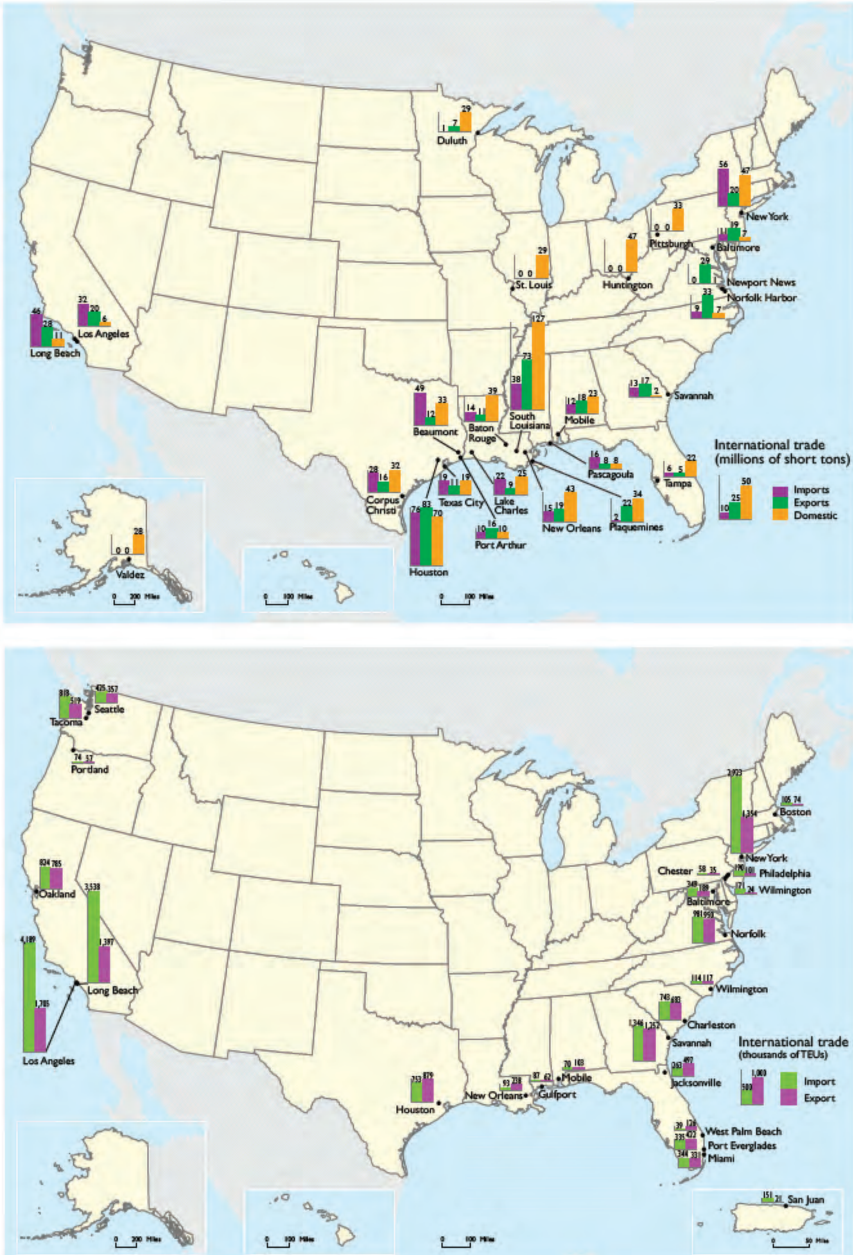


FIGURE G-27 Top 25 ports by tonnage, 2013 (top); top 25 water ports by containerized cargo, 2014 (bottom).
SOURCE: FHWA.

U.S. agricultural production overall (Niemeier et al. 2013). However, increases will not be uniform across the country because of the changes in temperature and/or precipitation, control-crop production location, and combination of crops that are planted. Climate changes from 1970 to 2010 explain up to 50 percent of the shift in crop production location for that period. For example, from 1990 to 2009, North Dakota wheat acres fell from 60 to 45 percent of cropland while corn acres doubled and soybean acres increased 10-fold. Under projected future temperature and precipitation values, almost all major crops in U.S. production regions will shift north and east (Cho and McCarl 2017). The production of corn and soybeans is expected to continue to increase in the northern regions and decrease in southern regions (Attavanich et al. 2013).

As agriculture relocates or changes crops, transportation needs will be affected. For example, corn yields by volume and weight are much higher than wheat. Thus, increased grain transport is anticipated in the North. The transport mode will shift away from barges to trucks and rail, primarily due to increasing distance from the river system (see Figure G-28). Truck transport increases by up to 34 percent are predicted. Climate change is also expected to lengthen the navigation season and lower Great Lakes levels. These changes will likely shift the transport season to later in the year and add modest additional increases to truck transport (Attavanich et al. 2013).

Regions identified for road expansion and improvement to accommodate increased truck traffic include the Upper Mississippi River in Minnesota, the Ohio River, the Arkansas River, and the Lower Mississippi

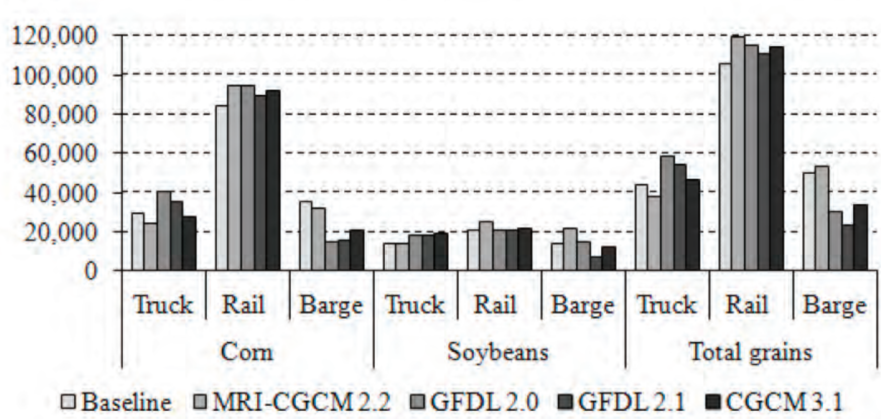


FIGURE G-28 Grain shipment modes of transportation due to climate-induced shifts in crop production patterns under baseline (2007–2008) conditions and future (2050) conditions using output from four different global climate models. Quantities are in 1,000 metric tons.
SOURCE: Figure S1 in Attavanich et al. 2013.

River in Kentucky. Truck routes in northern regions that connect highways with ports and rail terminals may also need to be improved. Target regions include roads in northern parts of Ohio leading toward ports on Lake Erie and roads in New York, Ohio, and Pennsylvania leading to Atlantic ports at Norfolk, Virginia (Attavanich et al. 2013).

SYNTHESIS AND CONCLUDING REMARKS

Climate change is happening; it is happening now, it is already affecting the Interstate Highway System, and it will do so increasingly in the future. We have high confidence that rising sea levels, increased storm surges, warming summers, and new temperature extremes will affect the Interstate System's routine performance as well as the ability for the Interstate System to perform during extreme events. The Interstate Highway System is already highly vulnerable to extreme precipitation and inland flooding. In some regions, including the Northeast, Pacific Northwest, and Northern Great Plains, climate change–induced alterations to the magnitude, duration, and intensity of rainfall as well as changing antecedent conditions and precipitation transitions from snow to rain will likely challenge system performance. Beneficial aspects of climate change that result from moderating winter conditions include a longer construction season and reduced winter maintenance and wear. Beyond direct impacts to the Interstate System, secondary environmental impacts and impacts to other transportation modes and other sectors may further exacerbate challenges to the Interstate Highway System. Information regarding the Interstate Highway System and climate change impacts were largely drawn from several qualitative vulnerability studies conducted at a national level, numerous local and state vulnerability studies that provide an uneven approach to assessing local assets and systems, and a relatively sparse academic literature. Despite the recent progress, there are significant gaps. Relatively little adaptation planning and implementation have occurred except where disasters provided the impetus for change. Nationally consistent, reliable indicators of vulnerability and societal impacts are needed to provide actionable, quantitative measures for Interstate System planning, design, and operations and maintenance activities (Savonis et al. 2014).

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Abbreviations

AMAP	Arctic Monitoring and Assessment Programme
Caltrans	California Department of Transportation
EPA	Environmental Protection Agency

FHWA	Federal Highway Administration
GAO	Government Accountability Office
IPCC	Intergovernmental Panel on Climate Change
NASEM	National Academies of Sciences, Engineering, and Medicine
NCEI	National Centers for Environmental Information
NRC	National Research Council
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation
USGCRP	U.S. Global Change Research Program

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Appendix H

Summary of HERS, NBIAS, and PHT Modeling Tools

The two models used by the Federal Highway Administration (FHWA) to address future investment and performance issues are the Highway Economic Requirements System (HERS) and the National Bridge Investment Analysis System (NBIAS). The HERS[1] and NBIAS[2] models are used to forecast the future conditions and performance of highways in the Conditions and Performance Report, known as the C&P Report, which the U.S. Department of Transportation (U.S. DOT) submits to Congress every 2 years. The C&P Report fulfills the mandate for a report on future highway investment requirements that the Congress first established in 1965. The HERS modeling tool analyses highway sections that are not related to bridges and structures while NBIAS specifically models bridges and structures. The information about HERS as well as the related graphics and tables provided in this appendix are drawn from FHWA technical reports and related articles (Coley and Lwin 2014; U.S. DOT 2005). The information related to NBIAS is derived from C&P materials and publications by experts (Coley n.d.; FHWA and FTA 2016; Robert and Gurenich 2008; Robert and Sissel n.d.).

A third tool, the Pavement Health Track (PHT) analysis tool, also developed under the sponsorship of FHWA, is an engineering software tool for determining and reporting the health of pavement networks in terms of

[1] This appendix describes HERS 2015. FHWA is working on new enhancements to the HERS, which are not described here.

[2] This appendix describes NBIAS version 4.0. FHWA is working on new enhancements to the NBIAS, which are not described here.

pavements remaining service life (RSL). In this appendix, the information about PHT is based on material from the PHT User's Guide (FHWA 2013b) and Technical Information report (FHWA 2013a).[3]

In particular, PHT allows users to determine pavement health in terms of pavement life, ride-ability, or distress by pavement types under various environmental and administrative conditions, such as climate, functional classification, or rural/urban environment, on projects, corridors, and networks.

HIGHWAY ECONOMIC REQUIRMENTS SYSTEM (HERS)

HERS estimates national investment needs relative to user-specified targets. It, however, does not analyze how much funding should be raised at different levels of government. HERS has many practical applications for a transportation agency, including long-range planning, programming, performance measures management, needs assessments, and legislative decision support. At its most basic, HERS addresses the questions: "if we invest in highways at a certain level, what are the performance implications?" and vice versa, "if we are looking for a specific level of performance, what level of investment is needed?" It does so by predicting future conditions and implementing a variety of alternative improvements to address deficiencies. In both cases, deficiencies are first defined, then improvements are developed to address the deficiencies. In the course of selecting improvements, the expected impacts of those on the system are evaluated. Through this process, HERS estimates three kinds of benefits that possible highway improvements have if implemented: benefits to highway users in the form of travel time, operating vehicle costs, and safety; benefits to highway agencies in the form of reduced maintenance costs; and finally the benefit of reduced vehicle emissions. In HERS, the selection of recommended improvements is based on benefit-cost analysis of alternatives. Table H-1 summarizes the investment categories that HERS evaluates.

Capital improvements that are not modeled in HERS include safety improvements such as rumble strips, safety edges, median treatments, signalized intersection improvements, and guardrails. Landscape improvements are also not included in the modeling.

The underlying data for the HERS model are gathered from the Highway Performance Monitoring System (HPMS). HPMS is a national-level highway information system that includes data on the extent, condition, performance, use, and operating characteristics of the nation's highways. The HPMS database covers highways eligible for federal aid, that is, all

[3] While this section of the appendix provides only a brief summary of PHT, more detailed information can be found at https://www.fhwa.dot.gov/pavement/healthtrack.

TABLE H-1 HERS Investment Categories and Improvements

Categories	Improvements Evaluated
Pavement Preservation*	Resurfacing
	Reconstruction (pavement surface layers only)
Increasing Interstate Capacity to Carry Traffic	Additional travel lanes
	Wider lanes
Operations and Intelligent Transportation Systems	Ramp metering
	Incident management
	Variable speed limits
	Integrated corridor management
	Weather management

*Most pavement preservation, capacity expansion, and operational improvements projects also improve safety.

roads except local roads and rural minor collectors. Within the database, the highway network is divided into sections homogeneous over their length. The sections sampled for the HPMS represent short sections varying in length between 1 and 20 miles approximately and are geographically scattered. The sample size, however, is designed to achieve target level of statistical precision for the purpose of estimating vehicle-miles traveled (VMT) by state and highway type. Overall, the database includes detailed data of more than 100,000 randomly sampled sections. The data are collected annually by state departments of transportation (DOTs) and submitted to FHWA. For conducting technical analyses, HPMS comprises two basic parts:

1. Universe data—a relatively limited number of data items for all mileage classified as Interstates, freeways, arterials, and collectors.
2. Sample Panel data—a large set of data items for a sample of highway mileage classified as Interstates, freeways, arterials, and collectors. Many states "oversample" and provide nearly complete coverage for the Interstate System. Nationally, about 50 percent of all Interstate mileage is covered by the Sample Panel. HERS uses this Sample Panel data.

Table H-2 reviews the HMPS inputs into HERS. HERS is not a network model. It does not forecast demand for travel between origins and destinations, and it does not assign that demand to paths through the network, such as is done with the travel demand forecasting models used by

TABLE H-2 HPMS Inputs into HERS

TRAFFIC Inputs	
Average Annual Daily Traffic (AADT)	Base year level
	Forecast for future year (usually current year plus 20)
	Vehicle composition— Light-Duty Vehicles (small autos, medium autos, 4-tire trucks) Single Unit Trucks (6-tire trucks and 3–4 axle trucks, including buses) Combination Truck (4-axle combination and 5-axle combination)
	Directional and "K" Factors
Traffic Control Devices	Signals—number and type
	Stop signs—number
GEOMETRY Inputs	
Widths	Lanes, median, shoulders
Types	Median and shoulders
Grades	Horizontal and vertical
Improvement history	
Widening feasibility	
PAVEMENTS Inputs	
Surface and base	Types and thickness
Pavement roughness and present serviceability rating	
New distress measures	Rutting
	Faulting
	Fatigue cracking
	Transverse cracking
OTHER Inputs	
Number of through lanes	Peak versus counter peak
Turn lanes	
Located on National Highway System?	
Speed limit	

metropolitan planning organizations (MPOs) and state DOTs. Rather, each HPMS section is considered in isolation. Traffic growth rates developed by the states when they submit HPMS are used to forecast future traffic on each segment.

HERS conducts its analysis through a set of time frames that are equal in length; these are called funding periods and involve 5-year increments. For example, if estimates are needed for a 20-year overall analysis period, as in the case for the C&P reports, the HERS analysis is split into four 5-year funding periods to evaluate the investment needs and level of performance of the evaluated road infrastructure.

HERS evaluates each HPMS section individually. In doing so, it screens for deficiencies by engineering technical standards and identifies potential remedial improvements. HERS operates in what could be called a funding-constrained mode, meaning that it recommends the most cost-beneficial of the improvement candidates. The first step is to compare conditions on the section to a set of deficiency values to screen for sections that are candidates for improvement. If a section is deficient, HERS begins its benefit-cost analysis. In general terms the analysis process consists of the following:

- A set of improvements are defined to address deficiencies on the highway section. Multiple deficiencies are allowed. Deficiencies are related to geometric conditions (cross-section and alignment), congestion, and pavement condition.
- For each potential improvement, the impacts of the improvement on performance are estimated; these impacts are the benefits. Costs for the improvement are derived from unit cost information and the size of the improvement. HERS then selects the improvement with the best benefit-cost ratio (BCR).
- HERS keeps track of improvement costs in a given pass through the data. In that given pass, it also records the new enhanced performance for the sections with the new implemented improvements.
- In the next pass through the data (in the 5-year funding period), performance for the section is updated to account for traffic growth and pavement deterioration. The whole process is then repeated to evaluate any improvements that might be warranted in the new funding period.

In addition to the main HERS engine that conducts the benefit-cost analysis, HERS includes a number of preprocessors and submodels that enhance the capabilities of the primary engine. The preprocessors perform their analysis outside of HERS and ultimately provide their results as an input file for HERS. On the other hand, the submodels are internal to HERS and their function is to perform specialized functions to enhance the overall analysis. Preprocessing calculations include, for instance, validation checks and corrections to HPMS input data. For example, data items for truck traffic are frequently missing within the HPMS database; this particular preprocessor fills this gap by providing 20-year projections for these measures. HERS also includes an Operational Improvements preprocessor that assigns operational improvement strategies to HPMS sections based on congestion level. The Operational Improvements preprocessor does the impact analysis without subjecting its selected improvements to benefit-cost analysis. In fact, the preprocessor is a separate model that produces an input file for HERS that includes adjustment factors that account for increased capacity, reduced delay, reduced incident duration, and improved safety. Therefore, with the Operations Improvements preprocessor engaged, HERS uses an HPMS dataset that already has operations strategies deployed. Any additional improvements that HERS assigns is done assuming that these operational strategies are in place and have improved capacity and safety or both to some degree.

Through its analysis, HERS monetizes benefits from reductions in travel time, vehicle operating costs, crashes, emissions, and highway maintenance costs. To analyze these and in addition to the main HERS engine, HERS also uses a variety of submodels already embedded within the program. These submodels have been derived by adapting models used by state and local agencies to perform highway planning studies. However, simplification and the use of default values have been necessary to make these models work with the type of data in HPMS; state and local agencies usually have more data available to them when they conduct project level analysis. The analyses conducted with these submodels include the following:

- Travel time and travel time reliability prediction are based on Highway Capacity Manual procedures. Both business and personal travel are considered in this analysis. Costs that are considered in this type of analysis might include depending on the type of travel, value of time per person, average vehicle occupancy, vehicle capital costs, and inventory costs.
- Crash prediction is based on relationships found in the safety literature.
- Emission prediction is based on the Environmental Protection Agency's MOVES model.
- Vehicle operating costs are based on relationships for speed and pavement condition. They take into account fuel, motor oil, tire wear, maintenance and repair, and mileage-related depreciation.

Figure H-1 illustrates the main calculations and their interrelationship within HERS.

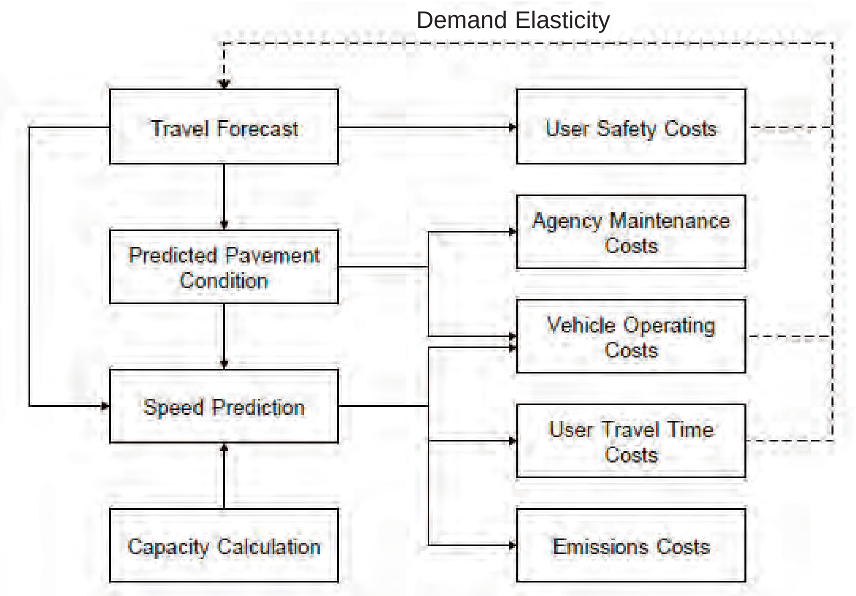

FIGURE H-1 Calculation interrelationships within HERS.
SOURCE: U.S. DOT 2005.

In its calculations, HERS differentiates between three different types of costs: costs to both society and users (e.g., travel time), costs to society but not to users or externalities (e.g., damage due to emissions), and cost to users but not to society (e.g., fuel taxes). This differentiation is key in order to quantify the benefits of specific highway improvements, as well as predicting the behavior of users subsequent to implementation of a given improvement.[4]

HERS can perform three different kinds of analysis:

- Analysis where the funding is constrained. HERS will compute the highway performance when highway improvements are constrained by the available budget.
- Analysis where the performance is constrained. Here HERS will provide information on the funding needed to reach a specific level of performance for the highway network under study.
- Analysis where the benefit-cost ratio (BCR) is greater than a specified threshold. In this case, HERS will compute both the funding and the level of system performance for the given BCR.

[4] Although HERS is not a network model, it does contain a simplified procedure for addressing future demand; elasticities are used to adjust traffic growth based on congestion level.

Another feature within HERS is that of a provision that allows for forcing the model to improve unacceptably deficient highway sections even if the BCR is not met. These are known as "mandatory improvements." If this feature is not used in a given analysis, the analysis is run without mandatory improvements (this is the basic analysis). Figure H-2, captured from the *HERS ST Technical Report 2005*, illustrates the overall basic processes (i.e., without mandatory improvements) for runs with a minimum BCR and runs with either constrained budgets or constrained performance. Figures H-3 and H-4 illustrate the budget and performance constrained analyses when mandatory improvements are implemented.

By the end of the analysis, HERS produces an extensive set of statistics that describe the estimated state of the road system under evaluation, the

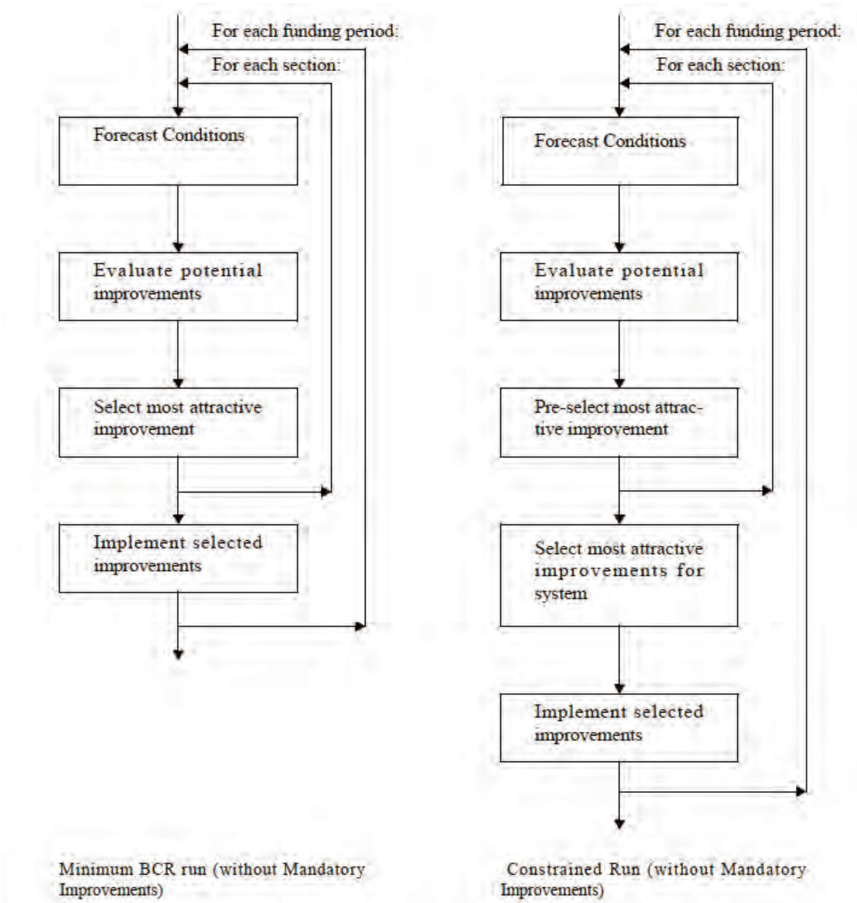

FIGURE H-2 Analysis process flow for runs without mandatory improvements.
SOURCE: U.S. DOT 2005.

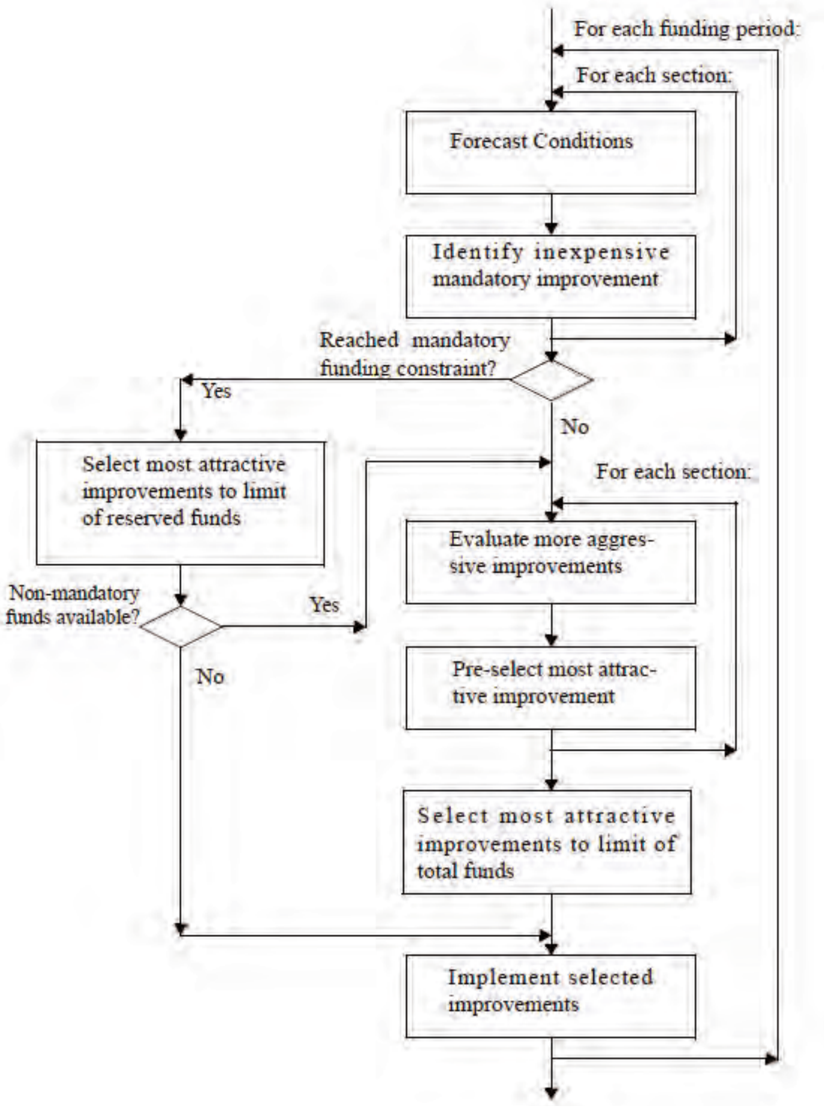

FIGURE H-3 Analytical process for analyses for constrained funds and with mandatory improvements.
SOURCE: U.S. DOT 2005.

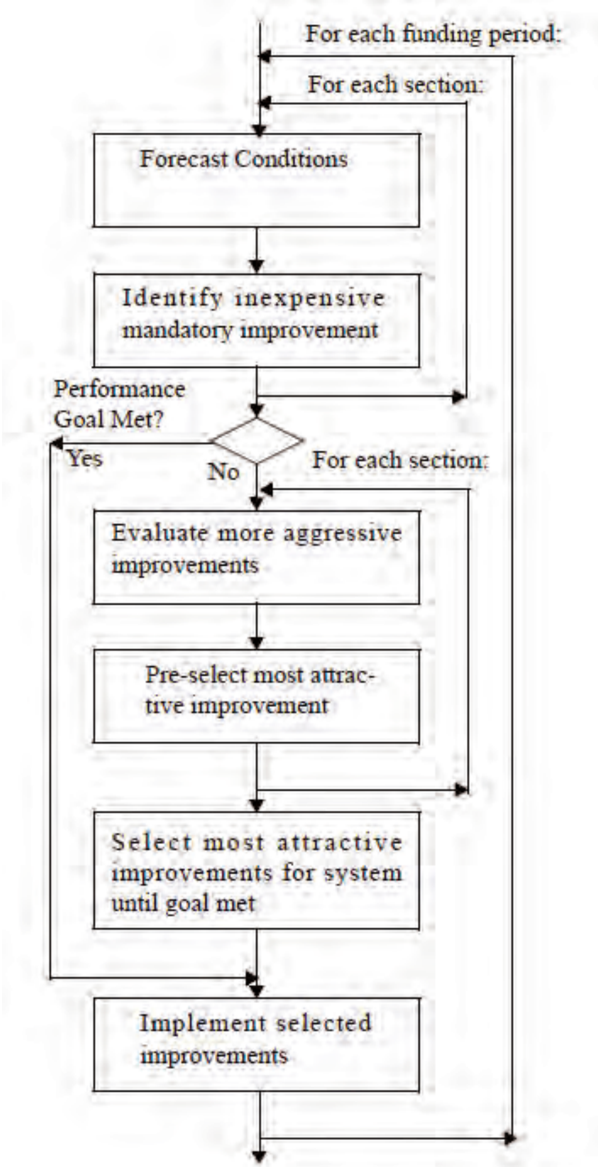

FIGURE H-4 Analytical process for analyses for constrained performance and with mandatory improvements.
SOURCE: U.S. DOT 2005.

history of each section evaluated, the costs and benefits (i.e., performance measures) of the implemented improvements, and the history of each section. HERS reports the results of the analysis in three different formats with specific focuses: System Condition format, Deficiency Reporting format, and By-Improvement-Type format.

With regard to system condition, HERS produces a report that includes the following information:

- A summary of the state of the system at the start of the run,
- A summary of the state of the system at the end of each funding period,
- A summary of how the system is predicted to change between the beginning and the end of each funding period as well as for the overall analysis period, and
- Detailed information of the costs and benefits associated with the selected improvements for each funding period and for the overall analysis period.

The output set of data for the three summaries (items 1 through 3 above), for example, includes the following items:

- Miles in the system;
- Average present serviceability rating (PSR) of pavement conditions (paved sections only);
- Average international roughness index (IRI) (inches per mile, paved sections only);
- Lane width;
- Right-shoulder width;
- Shoulder type;
- Surface type;
- Horizontal alignment;
- Vertical alignment;
- Average speed;
- Peak-hour volume/capacity ratio;
- Congestion delay (hours per 1,000 vehicle-miles);
- Total delay (hours per 1,000 vehicle-miles);
- Total VMT;
- Travel-time costs (dollars per thousand vehicle-miles);
- Operating costs, listed for all vehicles combined and separately for four-tire vehicles and for trucks (dollars per thousand vehicle-miles);
- Crash costs (dollars per thousand vehicle-miles);
- Total user costs, which is a summation of travel-time costs, operating costs for all vehicles, and crash costs (dollars per thousand vehicle-miles);

- Number of crashes (per 100 million vehicle-miles);
- Number of injuries (per 100 million vehicle-miles);
- Number of fatalities (per 100 million vehicle miles);
- Annual maintenance costs (dollars per mile);
- Average cost of pollution damage (dollars per 1,000 vehicle-miles); and
- Percentage of total VMT on roads not meeting the user-specified thresholds.

The second format for output data is the Deficiency Summary report. This report outlines the deficiencies present in the system at the start of the funding period and the overall analysis period, as well as the effectiveness that the recommended improvements had in reducing those deficiencies. The measures reported in this report include the IRI, PSR, volume-to-capacity (V/C) ratio, lane width, shoulder width, surface type horizontal alignment, and vertical alignment.

Finally, HERS produces an output file that contains the data for all the sections that HERS recommends for improvement during the funding period. The data are organized by functional class[5] and improvement type. In this report, HERS includes summaries of the following:

- Capital costs for all recommended improvements for each section at each funding period and for the overall analysis period,
- Initial costs of preservation improvements,
- Initial cost of capacity improvements,
- Lane-miles improved,
- Lane-miles of mandatory improvements selected on a priority basis to address unacceptable conditions,
- Lane-miles of non-mandatory improvements not selected on a priority basis,
- Net present value of the residual value of all improvement,
- Average benefit-cost ratio of recommended improvements,
- Total benefits in the last year of the period,
- Maintenance costs savings in the last year of the period,
- User benefits in the last year of the period,
- Travel time savings in the last year of the period,
- Operating cost savings in the last year of the period,
- Safety benefits in the last year of the period,
- Crashes avoided in the last year of the period,

[5] HERS considers nine functional classes of roads: rural Interstate, other rural principal arterial, rural minor arterial, rural major collector, urban interstate, other urban freeways/expressways, other urban principal arterials, urban minor arterials, and urban collectors.

- Injuries avoided in the last year of the period,
- Lives saved in the last year of the period,
- VMT for improved sections in the last year of the period,
- Emissions costs savings in the last year of the period, and
- Lane-miles added to the system through widening improvements.

HERS STRENGTHS AND WEAKNESSES

The HERS model has both strengths and weaknesses in its application to the Future Interstate study. Its strengths include

- HERS is national in scope and Interstates throughout the country can be analyzed with a consistent set of data and procedures.
- HERS's underlying data source (HPMS) is the same geometric, traffic, and pavement data used by state DOTs in their own investment needs analyses. Likewise, HERS's analytical procedures are based on the same methods in widespread use by state DOTs and MPOs for needs analyses.
- HERS provides insight into the tradeoffs between investment and performance, which is critical to informing investment decisions.
- A state-level version of HERS has been developed and several state DOTs have used it in conducting their needs analyses.

However, HERS has several limitations that need to be considered and, when possible, addressed by other means. First, improvement types in HERS are limited to pavement surface treatments or reconstruction of the top pavement layers. Safety improvements are limited to lane and shoulder widening and horizontal curve flattening. The HPMS contains no safety data related to some road features. HERS models each HPMS section individually, without regard for system effects. The model focuses on capital expenditures and user costs, and it has a long-term investment perspective consistent with the traditional federal-aid program focus. With that emphasis, the model does not address administrative costs or the cost of planning. The analyses are applied to existing facilities and do not take into account new highway alignments.

HERS must use the traffic forecasts provided exogenously to calculate future demand. It therefore cannot account for shifts in demand to due changes in the network in the same way that a travel demand forecasting model does. HERS does contain a simplified procedure for addressing this issue—elasticities are used to adjust traffic growth based on congestion level. So, if an improvement reduces congestion, traffic growth will be slightly higher than it otherwise would be. However, this approach does not begin to address the issue of where the additional demand originates, or where it goes if it is diverted. Finally, the HERS approach to project selection based on strict benefit-cost analysis may not be fully representative of how agencies actually select and design projects. State and local agencies also use other criteria for selecting projects and their design, such as total cost and the impact on sustainability, the economy, and quality of life. The great variation in engineering practices and policy drivers in various regions (some would argue rooted in the funding availability for public works) can strongly influence whether the economic logic behind the HERS algorithms is accepted as a "good match" with decision making and governance goals.

For all of these limitations, the analysis techniques included in HERS represent a framework that captures a large amount of future highway needs. The use of HERS is a significant improvement over the survey-based "wish lists" that have dominated many so-called "needs studies" or even the slightly more rigorous catalogues that compare current systems to engineering standards without regard to economic principles. At the national level, the range and scale of investment needs findings are important; and HERS is the only available methodology at that scale that is comprehensive, systematic, and peer reviewed.

National Bridge Investment Analysis System

NBIAS is an investment analysis software platform used to analyze future bridge investment needs and their performance. The program has historically been used to evaluate the backlog of needs, distribution of needed improvements, aggregate and user benefits, and physical measures of bridge condition, among others. Some of the questions that NBIAS can address include, for example, "what level of spending is required annually to maintain current bridge conditions over the next 20 years?" or "what user benefits might be achieved with a given set of improvement investments?" To answer these questions, NBIAS simulates bridge deterioration, functional needs, traffic, and costs; and it does so for each bridge for each year in a multi-year analysis cycle. Therefore, although the principal use of NBIAS is as a network-level analysis tool, the completeness of its analysis also permits to use its results for diagnostics purposes at the bridge-level.

NBIAS was designed to use the National Bridge Inventory (NBI) information. The NBI is a federally mandated database of bridge inventory and condition for all bridges covered by the National Bridge Inspection Standards[6] and compiled by state DOTs for submission to FHWA. The NBI has many positive features: it is a complete census of bridges so the results do not have to be extrapolated, there is little lag time between

[6] The NBI database includes a thorough inventory and condition information of all bridges more than 20 feet of span in the U.S. public road system.

collection and availability, and the data are collected by direct observation of bridge engineers. The data are gathered through these inspections every 2 years; in some instances, however, states choose to inspect certain bridges more often. In either case, the states submit their data to the NBI on an annual basis. Because the NBI covers all bridges[7] in all U.S. public roads, the NBIAS analysis results provide a complete picture of the performance and the benefit-cost analysis for bridges.

NBIAS was originally developed by FHWA as a national version of the Pontis Bridge Management System.[8] As such, NBIAS borrowed from the fundamental modeling structure of Pontis. Subsequently NBIAS has been improved with additional modeling methodologies from the Florida DOT. Other improvements done over time include revisions to support the integration of NBIAS results with HERS for a comprehensive highway investment needs analysis.

NBIAS is composed of two modules:

- The Analytical Module, which allows to create an NBIAS database from NBI files, specify technical parameters, and define and run budget scenarios, and
- The "What-If" Module, which conveys the analysis results via interactive screens and reports. These can be displayed for selected scenarios.

The NBIAS Analytical Module computes both preservation and functional improvement needs. The modeling to evaluate preservation needs aims at determining the preservation policy that best minimizes the long-term cost of maintaining each bridge element in the state of good repair. The evaluation of functional improvements includes the following actions: widening of existing lanes and shoulders, strengthening, bridge raising, and bridge replacement.

The investment of functional improvement needs are calculated by applying user-specified standards[9] to the bridge inventory and then conducting a benefit-cost evaluation, while the investments needed for preservation are determined by applying a set of deterioration and cost models to determine the appropriate repair and rehabilitation actions while minimizing agency costs. We summarize key points about both modeling goals below.

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[7] The NBI covers more than 600,000 highway bridges in the U.S. public road system.

[8] Licensed by the American Association of State Highway and Transportation Officials (AASHTO).

[9] Standards for functional improvements include those for lane width, load rating, and vertical and horizontal clearances.

In order to determine whether a bridge needs a functional improvement, NBIAS applies two sets of business rules:

- Functional improvement policies. These are based on threshold values for lane width, shoulder width, load rating, and vertical clearance.
- Rules derived from calculating sufficiency ratings and structural deficiency (SD) or functionally obsolete (FO) status. Any issue that causes a bridge to be classified as SD or FO or results in a reduction of sufficiency rating also prompts a need for improvement.[10]

The analyst has the option of using one of these rules or both when conducting analyses. Once the possible need for improvement is identified, NBIAS evaluates if such improvement is feasible from the engineering perspective or a last resort if complete bridge replacement is the only option. The rules for such case are specified based on the bridge SD/FO status, age, health index, and sufficiency rating. Once NBIAS evaluates the feasibility of a functional improvement or recommends a complete reconstruction, it proceeds to calculate the costs and the benefits of implementing the improvement. The following bulleted points specify the basis for computing the benefits for specific improvements:

- Widening needs are computed based on reduction of crash on the bridge,
- Strengthening and raising needs are evaluated based on the reduction of truck traffic detoured around the bridge, and
- For bridge replacement, the benefits are based on both reduction in accidents and truck traffic detours. The reduction in life-cycle cost is also included as a benefit, since a bridge replacement restores all bridge elements to the state of best condition.

Unlike functional improvements described above, bridge preservation needs are analyzed at the level of each bridge element. The NBI database, however, represents information at the bridge component-level.[11] And thus, to conduct its analysis, once NBIAS imports the NBI data, it converts them

[10] A couple of examples for these rules include, for instance: A deck rating in the NBI of less than 6 triggers a potential widening need, or if the bridge is located in the Strategic Highway Network and its vertical clearance is less than 4.87 meters this is identified as a vertical clearance deficiency and might trigger the need to raising the bridge.

[11] Bridge components represent the major structural portions or units of a bridge, such as deck, superstructure, and substructure. Bridge components are composed of multiple bridge elements. For example, the superstructure is composed of a series of beams, girders, stringers, gusset plates, or other elements.

to element level information data, through what is called, a reverse translator. The reverse translator uses a set of synthesis, quantity, and condition (SQC) models to approximate the element composition of each bridge. It then subjects each of those elements to a set of analyses using deterioration algorithms and cost models for different functional improvements and preservation actions. Specifically, it uses the deterioration modeling approach[12] derived from Pontis, along with optimization to determine the optimal set of improvement actions for each bridge element based on its condition. In addition to conducting calculations for each element, NBIAS adjusts for information relevant to each state using adjustment factors. The preloaded deterioration factors and costs in NBIAS are adjusted for nine different climate zones and with cost adjustment factors that are specific to each state. These costs are based on bridge replacement costs reported in the specific states. As with HERS, NBIAS recommends corrective actions based on benefit-cost analysis and to meet either specified performance metrics or a limited budget. Ultimately the goal of the benefit-cost analysis is to recommend the best improvement option that minimizes the user and agency costs over time.

For every bridge analyzed, NBIAS generates a set of project alternatives that merges the results of potential preservation and functional improvements and screens the alternatives by BCR. The project options that are considered for recommendation are then organized by incremental BCR. At this point, NBIAS apportions funding to improvement alternatives until either the total budget is reached (if the analysis is budget-constrained[13]) or a minimum level for incremental BCR is achieved.[14] Finally, it predicts the effect of the selected improvements on bridge conditions and the analysis cycle is then repeated by using the new bridge conditions as the starting point. The simulation period might between 1 and 50 years. As time steps (of 1 year) are taken, NBIAS allows the analyst to use either linear or exponential traffic growth projections. Figure H-5 provides a schematic of the analytical process in NBIAS as illustrated in Robert and Gurenich (2008). Following this basic structure, NBIAS can perform parameterized analyses when the algorithm executes multiple analysis steps, each consisting of a simulation over time at a different budget, budget growth rate, or benefit/cost cutoff.

[12] It specifically uses Markov chain methodology for modeling bridge element deterioration. Details about the methodology can be found in Fu and Devaraj (2008).

[13] In this case, the analyst must specify lower and upper limits for the annual budget.

[14] When analysis is based on cutoff BCR, the analyst specifies the upper and lower limits for the cut-off BCR and the number of parametric steps. NBIAS then assumes an unlimited budget and recommends improvements until the BCR for the potential improvements fall outside of the benefit-cost limits.

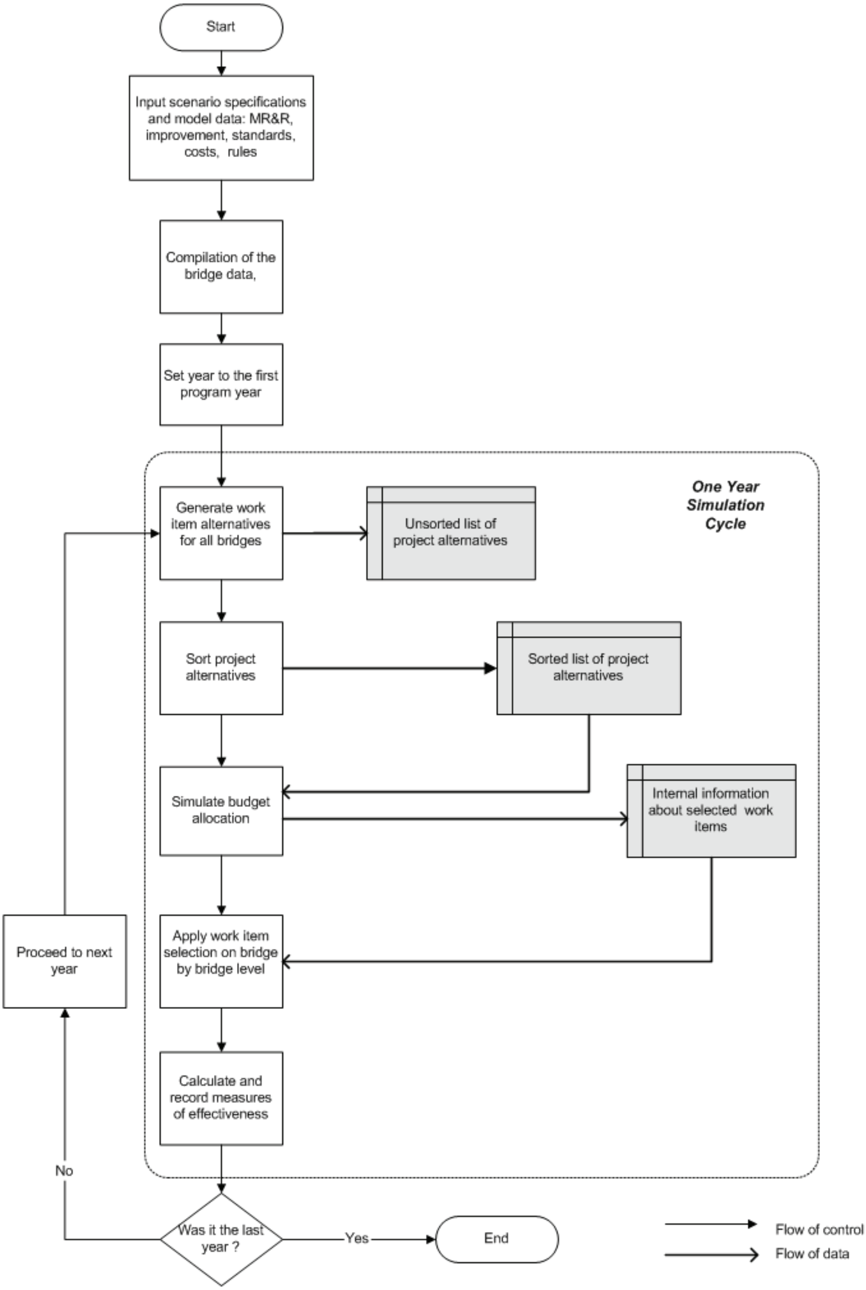

FIGURE H-5 Schematic of NBIAS analytical process.
SOURCE: Robert and Gurenich 2008.

The output of parametric runs is a four-dimensional array of results with the following dimensions:

- Measures of effectiveness,
- Simulation year,
- 26 bridge categories (considered from 13 functional classes of bridges either in/off the NHS or in/off the SHN), and
- N+2 parametric steps.

NBIAS reports analysis results for 206 measures of effectiveness (performance measures) that can be grouped into needs, work and backlog, benefits, BCR, NBI condition ratings, health index, sufficiency ratings, and structurally deficient/functionally obsolete bridges. Examples of measures of effectiveness reported include among others:

- Investment needs—Annual recommended actions for each bridge analyzed. Reported in dollars and bridges;
- Money spent;
- Additional costs of postponed investments;
- Work performed;
- Backlog of needs—Reported in dollars and bridges;
- User benefits;
- Distribution of deck, superstructure, and substructure ratings;
- Percentage of deficient bridge by deck area; and
- Structural deficient bridges.

NBIAS reports two kinds of benefits: Obtained benefits as those that are understood as occurring during the NBIAS time simulation and potential benefits as those that could be attained if no budget restrictions exist.

NBIAS reports the results both in graphical and tabular formats. In addition to series of reports, the modeling results can be displayed through a set of interactive views that allow interpolating results between multiple analysis steps.

Pavement Health Track

As mentioned in the introduction of this appendix, the PHT is an engineering software tool that calculates the health of pavement networks in terms of pavements remaining service life (RSL). The software allows users to determine pavement health in terms of pavement life, ride-ability, or distress by pavement types under various environmental and administrative conditions, such as climate, functional classification, or rural/urban environment, on projects, corridors, and networks. PHT also offers state-of practice maintenance options to estimate the benefits of each pavement section improvement quantified in terms service life.

To conduct its calculations, PHT uses pavement performance models that are simplified versions of the more complex mechanistic-empirical (ME) models and procedures used in the Pavement Design Guide (PDG). The PHT maintenance model allows to measure the pavement performance under a maximum BCR or under constrained funding. PHT also supports "what if" scenario analyses under various pavement design parameters, traffic, and/or terminal distresses or performance indicators.

PHT calculates benefits based on the following assumptions (see Figure H-6):

- Straight-line depreciation is used to depreciate individual pavement sections over their service life.
- The post-treatment rate of depreciation remains the same.
- The initial service life of the pavement is the sum of the current pavement age and the RSL where the current pavement age is the difference between the current year of record and the original year of construction for new pavements; or the year of last improvement for rehabilitated pavements.

The PHT analysis engine receives highway data and parameter metrics and determines the pavement RSL in accordance with its implementation process presented in Figure H-7. As with HERS, the primary input relies on HPMS data with an extension for the State Pavement Management System (PMS) database. PHT also includes nationally calibrated matrix parameters

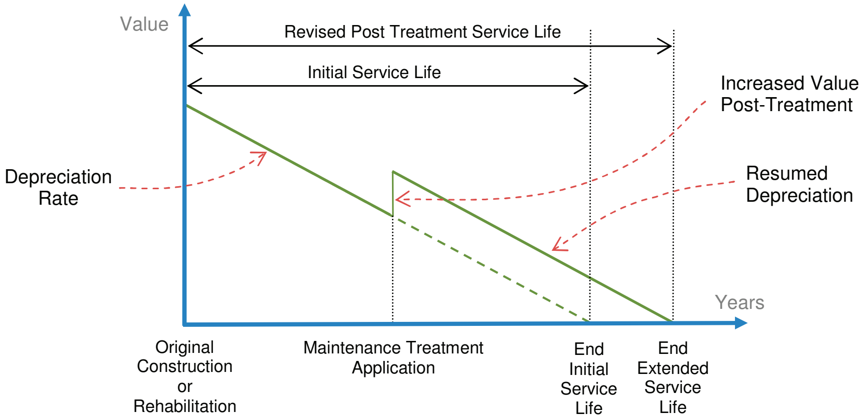

FIGURE H-6 Straight-line depreciation with maintenance treatment.
SOURCE: FHWA 2013b.

and level 3 (policy and planning) default values that are available through ME-PDG design software.

Tables H-3 and H-4 provide information on the type of improvements included in the PHT calculations for flexible, composite, and rigid pavements. Parameter metrics are used to control the analysis. The default parameter metrics used by the PHT analysis tool including the terminal thresholds, maximum service life, and default pavement estimates are

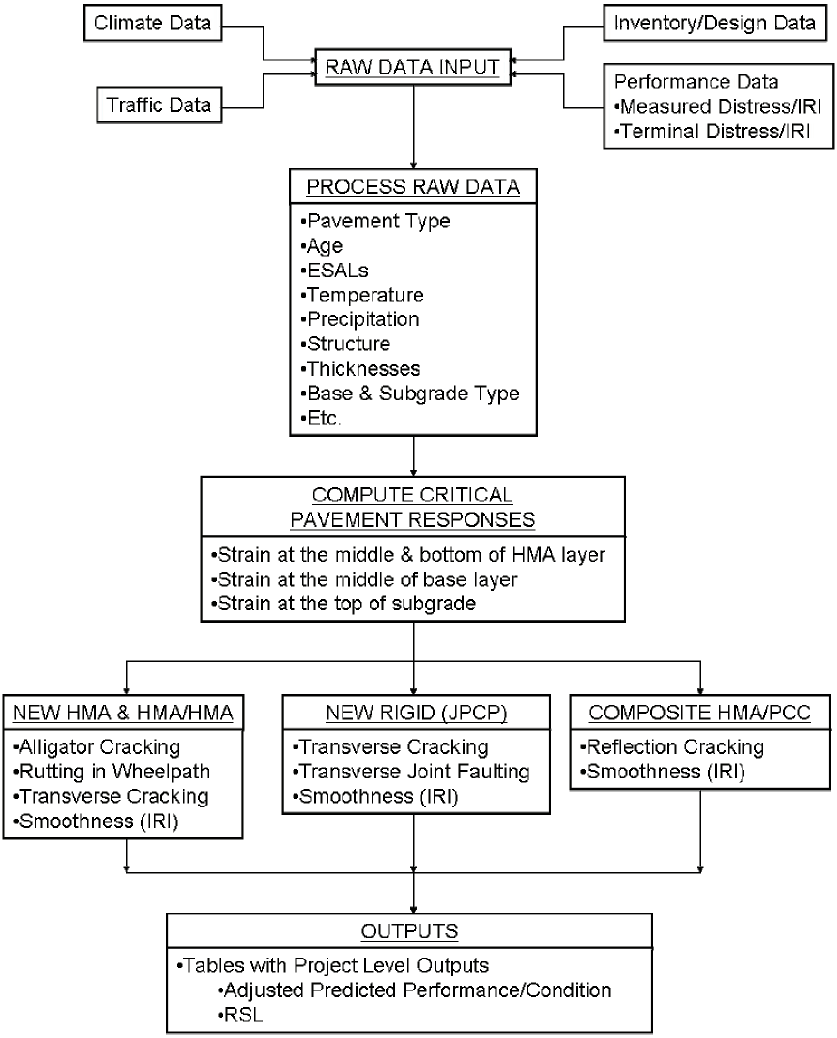

FIGURE H-7 RSL forecasting process.
SOURCE: FHWA 2013b.

TABLE H-3 Feasible Improvements for Flexible and Composite (AC) Pavements

	Interstate	Primary	Secondary
Surface sealing	N/A	N/A	RSL > 5 years Rutting < 0.35 in. Cracking Length < 2,500 Cracking Percent < 5% IRI < 150 in./mi.
Full depth patching with OR without grinding	RSL > 10 years Rutting < 0.25 in. Cracking Length < 250 Cracking Percent < 5% IRI < 125 in./mi.	RSL > 5 years Rutting < 0.25 in. Cracking Length < 1,000 Cracking Percent < 5% IRI < 150 in./mi.	RSL > 5 years Rutting < 0.35 in. Cracking Length < 1,000 Cracking Percent < 5% IRI < 125 in./mi.
Full depth patching with thin AC overly OR surface recycling	RSL > 10 years Rutting < 0.35 in. Cracking Length < 1,000 Cracking Percent < 10% IRI < 125 in./mi.	RSL > 5 years Rutting < 0.5 in. Cracking Length < 2,000 Cracking Percent < 10% IRI < 150 in./mi.	N/A
Major rehabilitation	RSL > 3 years Rutting < 0.35 in. Cracking Length < 2,000 Cracking Percent < 15% IRI < 150 in./mi.	RSL > 3 years Rutting < 0.5 in. Cracking Length < 2,000 Cracking Percent < 15% IRI < 150 in./mi.	RSL > 3 years Rutting < 0.75 in. Cracking Length < 2,500 Cracking Percent < 15% IRI < 175 in./mi.
New or reconstruction	RSL < 3 years Rutting > 0.35 in. Cracking Length > 2,000 Cracking Percent > 15% IRI > 150 in./mi.	RSL < 3 years Rutting > 0.5 in. Cracking Length > 2,000 Cracking Percent > 15% IRI > 150 in./mi.	RSL < 3 years Rutting > 0.75 in. Cracking Length > 2,500 Cracking Percent > 15% IRI > 175 in./mi.

SOURCE: FHWA 2013b.

TABLE H-4 Feasible Improvements for Rigid Pavements

	Interstate	Primary	Secondary
Functional repair	RSL > 10 years Cracking Percent < 10% Faulting < 0.15 in. IRI < 125 in./mi.	RSL > 10 years Cracking Percent < 10% Faulting < 0.15 in. IRI < 125 in./mi.	N/A
Surface seals & thin overlay	RSL > 10 years Cracking Percent < 1% Faulting < 0.1 in. IRI < 150 in./mi.	RSL > 10 years Cracking Percent < 1% Faulting < 0.1 in. IRI < 150 in./mi.	RSL > 10 years Cracking Percent < 1% Faulting < 0.1 in. IRI < 150 in./mi.
Major rehabilitation	RSL > 5 years Cracking Percent < 15% Faulting < 0.2 in. IRI < 175 in./mi.	RSL > 5 years Cracking Percent < 15% Faulting < 0.2 in. IRI < 175 in./mi.	RSL > 5 years Cracking Percent < 20% Faulting < 0.2 in. IRI < 175 in./mi.
Reconstruction	RSL < 5 years Cracking Percent > 15% Faulting > 0.2 in. IRI > 175 in./mi.	RSL < 5 years Cracking Percent > 15% Faulting > 0.2 in. IRI > 175 in./mi.	RSL < 5 years Cracking Percent > 20% Faulting > 0.2 in. IRI > 175 in./mi.

SOURCE: FHWA 2013b.

presented in Tables H-5 through H-7. The PHT software, however, allows the user to modify these values as needed.

The primary PHT outputs are the predicted distresses by pavement types, load applications, and weighted RSL. The results are tabulated in spreadsheet, charts, or maps by pavement type, RSL group (5, 10, 15 years, etc.), geographic location, and functional class.

HERS Default Parameters

Input Parameters

HERS and the HERS PreProcessor accept two broad types of input data:

TABLE H-5 Default Terminal Thresholds

Surface Type	Functional System	IRI	Cracking Percentage	Cracking Length	Rutting	Faulting
Rigid	Interstate	170	10%			0.15 in.
	Primary	220	15%			0.20 in.
	Secondary	220	20%			0.20 in.
Flexible	Interstate	170	20%	640 ft./mi.	0.40 in.	
	Primary	220	45%	800 ft./mi.	0.60 in.	
	Secondary	220	45%	1,270 ft./mi.	0.80 in.	
Composite	Interstate	170		100 ft./mi.		
	Primary	220		60 ft./mi.		
	Secondary	220		60 ft./mi.		

SOURCE: FHWA 2013b.

TABLE H-6 Default Maximum Service Life

Treatment Type	Years
New HMA	20
New PCC	30
Thick AC Overlay of AC Pavement	10
Thin AC Overlay of AC Pavement	6
Thick AC Overlay of PCC Pavement	10
Unbounded PCC Overlay of PCC Pavement	25
Bonded PCC Overlay of PXX Pavement	15
Thin AC Overlay of AC/PCC Pavement	6

SOURCE: FHWA 2013b.

TABLE H-7 Default Pavement Estimates

Pavement Estimate Category	State System On	State System Off
Last Overlay Thickness	3 in.	3 in.
Rigid Pavement Thickness	10 in.	10 in.
Flexible Pavement Thickness	8 in.	8 in.
Base Type	Granular	Granular
Base Thickness	4 in.	4 in.
Binder Type	AC-40 to AC-49	AC-40 to AC-49
Dowel Bar	Typically used	Typically used
Joint Space	20 feet	20 feet

SOURCE: FHWA 2013b.

- Control variables—Two control files (one each for HERS and the PreProcessor) contain processing directives that are likely to be specific to an individual analysis run. These files are:
  - Control inputs to the PreProcessor (PPSPEC.DAT)
  - Control inputs to the HERS executable (RUNSPEC.DAT)
- Parameter variables—Three parameter files contain data that are more likely to be unchanged between runs. These files are:
  - The improvement cost file (IMPRCOST.DAT) contains data items that define the costs of improving highway sections.
  - The deficiency level tables file (DLTBLS.DAT) defines the various condition levels that will prompt HERS to analyze a section for possible improvement.
  - The third parameter file (PARAMS.DAT) contains parameters covering the breadth of the HERS modelling process: the pavement model, operating cost components, the speed model, and the safety model, to name but a few.

PreProcessor Control Inputs

Tables H-8 through H-11 present the control inputs to the PreProcessor. The default values for the inputs are also presented.

HERS Executable Control Inputs

Tables H-12 through H-17 present the executable control inputs for HERS. The default values are also presented.

Improvement Cost Input

Table H-18 presents the default inputs for improvements costs in HERS.

Deficiency Level Tables Input

Finally, Tables H-19 through H-27 present the deficiency levels in HERS.

TABLE H-8 PreProcessor Control Inputs

Control Input	Description	Default Value
FILIN	Name of HPMS data file to be preprocessed	name.csv
FILOUT	HERS data file to be created	name.HRS
DSTOUT	Truck VMT distribution file to be created	name.DST
PCTNHS_FILENAME	Name of percent NHS file	Blank
INTYEAR_FILENAME	Name of intermediate year file to be used Blank if none–for federal use only	Blank
DO_INTYR_MID	Intermediate year middle switch specifying intermediate year to be used: • 0 = year specified • 1 = midpoint of Funding Period	1
LFP	Length of funding period	5
BASEYR	Base year of analysis (20xx)	16
PSRUPS	PSR for unpaved sections; passed to HERS as lower limit of pavement deterioration	0.10
CALCCAP	Coded capacity override switch • 0 – use coded capacities when supplied (normal case) • 1 – ignore all coded capacities	1
MAXGRW	Maximum AADT growth rate in %	25
GRSWITCH	Governs treatment of excessive growth rate • 1 – use default value below for every section with growth rate greater than the above maximum • 2 – interactively for every section with growth rate greater than the above maximum	1
DEFGRW	Default AADT growth rate (traffic growth rate for sections whose growth rate exceeds the maximum)	25
PGTMAX	Maximum percentage green time	80
PGTMIN	Minimum percentage green time	20
PGTRUR	Default percentage green time for principal arterials, minor arterials, and collectors, respectively	65, 50, 25
MAXR	Maximum AADT/Capacity ratio	16

TABLE H-8 Continued

Control Input	Description	Default Value
MRERR	Report excessive AADT growth rate switch • 0 – do not report AADT over capacity exceeded MAXR • 1 – print error message for sections with AADT over capacity ratio exceeding MAXR	1
MAXTCD	Maximum number of traffic control devices (stop signs and traffic signals) per mile	25
NTDERR	Governs generation of traffic control device error messages • 0 – do not report average number of stop signs and traffic signals per mile exceeded MAXTCD • 1 – print warning message for sections with average number of stop signs and traffic signals per mile exceeded MAXTCD	1
MINSPL	Minimum speed limit	15
MAXSPL	Maximum speed limit	80
RUERR	Governs generation of FC and RURURB error messages. Report inconsistent coding of RURURB • 0 = no • 1 = yes	1
AASWITCH	Alignment adequacy calculation switch • 0 – use coded values for alignment adequacy only if curves and grades are not reported • 1 – use coded values for alignment adequacy whenever values are supplied	1
PSRIRI	PSR/IRI indicator. When both PSR and IRI are coded: • 1 – Use PSR • 2 – Use IRI	2
OVERIDEMODE	• 1 – To provide exogenously supplied improvements through the following files • 0 – Otherwise	0

continued

TABLE H-8 Continued

Control Input	Description	Default Value
STATEIN	The name of the file that contains the user requested improvements. Includes CNTY and SECNUM as well improvements data. Leave the filename blank to run HERS-ST basic mode (i.e., no improvements)	name.csv
STATEOUT	The name of the produced file that is passed to the main HERS processor	name.bin
OPIMPS	Operational improvements control field. Each record in the file specified next will contain extra data. • 0 = don't read • 1 = 25 fields (5v×5fps) • 2 = 30 fields (6v×5fps) • 3 = 30 fields (6v×5fps) • 4 = 55 fields (5v×11fps)	0
OPIMPSFILE	Name of operational improvements file	name.csv
RampMeterIn	Indicates input (section and Opimps files) and output (.HRS file) format of Ramp Meter fields. • 12 – format through 2012, using a single integer code • 14 – format	14
RampMeterOut	Indicates input (section and Opimps files) and output (.HRS file) format of Ramp Meter fields. • 12 – format through 2012, using a single integer code • 14 – format	14
FAFFILE	Name of FAF data file	name.csv
FAFBASEYEAR	Base year for FAF data file	2005
FAFFUTYEAR	Future year for FAF data file	2035
SUTCTFCT	Ratio of single-unit trucks to combination trucks growth factors (FAF use only)	1.00
MAXTRKSHR	Maximum truck percentage allowed on any section	0.9
BaseTrkGrSU	Exogenous Demand Forecast Underlying Price Assumptions (EDFUPA) Annual Growth Rate: Single-Unit Trucks	1.01720
BaseTrkGrCM	Exogenous Demand Forecast Underlying Price Assumptions (EDFUPA) Annual Growth Rate: Combination Trucks	1.01460

TABLE H-8 Continued

Control Input	Description	Default Value
VOTbase	EDFUPA Value of Time Adj. Factors	See Table 1a
FUPRIbase	EDFUPA fuel price factors	See Table 1b
ADJVMTGR	VMT growth rate adjustment control field • 1 – Yes, adjust VMT Growth Rate per data below • 0 – No, use native HPMS growth	0
VMTGRGOAL	VMT goal control. Set VMT goal by • 1 – Entire System (All Functional Classifications) • 2 – Rural and Urban • 3 – Individual Functional Classifications	1
VMTINIT	Initial VMT table (12 entries)	See Table 1c
VMT20YEAR	VMT after 20 years table (12 entries)	See Table 1c
VMTGRINIT	Initial growth rate table (12 entries)	See Table 1c
VMTGRTARGET	Target growth rate table (12 entries)	See Table 1c

TABLE H-9 EDFUPA Value of Time Adj. Factors

	FP 1	FP 2	FP 3	FP 4	FP 5	FP 6	FP 7	FP 8	FP 9	FP 10
VOTbase	1.025	1.077	1.132	1.190	1.251	1.315	1.382	1.452	1.526	1.604

TABLE H-10 EDFUPA Fuel Price Factors

Funding Periods	Small Auto	Large Auto	Pickups/ Vans	6-Tire Trucks	3-Axle Trucks	3-Axle Semi	5-Axle Semi
Initial Conditions	1.000	1.000	1.000	1.000	1.000	1.000	1.000
FP 1	0.745	0.745	0.745	0.745	0.726	0.726	0.726
FP 2	0.861	0.861	0.861	0.861	0.869	0.869	0.869
FP 3	0.926	0.926	0.926	0.926	0.949	0.949	0.949
FP 4	1.007	1.007	1.007	1.007	1.048	1.048	1.048
FP 5	1.086	1.086	1.086	1.086	1.139	1.139	1.139
FP 6	1.178	1.178	1.178	1.178	1.248	1.248	1.248
FP 7	1.277	1.277	1.277	1.277	1.367	1.367	1.367
FP 8	1.385	1.385	1.385	1.385	1.497	1.497	1.497
FP 9	1.502	1.502	1.502	1.502	1.640	1.640	1.640
FP 10	1.629	1.629	1.629	1.629	1.796	1.796	1.796

TABLE H-11 PreProcessor Control Inputs—VMT

Functional Classification	Initial VMT	VMT After 20 Years	Initial Growth Rate	Target Growth Rate
Rural Interstate	243,918.609	342,687.938	1.01714	0.00000
Rural Other Principal Arterial	223,438.047	307,443.062	1.01609	0.00000
Rural Minor Arterial	148,438.078	195,590.938	1.01389	0.00000
Rural Major Collector	175,960.375	236,948.531	1.01499	0.00000
Urban Interstate	484,566.000	630,032.750	1.01321	0.00000
Urban Tollway	225,071.562	294,296.500	1.01350	0.00000
Urban Other Principal Arterial	455,866.250	591,690.312	1.01312	0.00000
Urban Minor Arterial	376,418.688	489,400.344	1.01321	0.00000
Urban Collector	179,698.891	238,341.797	1.01422	0.00000
All Rural	791,755.125	1,082,670.500	1.01577	0.00000
All Urban	1,721,621.375	2,243,761.750	1.01333	0.00000
All Functional Classifications	2,537,472.500	3,361,302.000	1.01416	1.01070

TABLE H-12 HERS Executable Control Inputs—RUNSPEC.DAT

Control Input	Description	Default Value
RUNNUM	20 character run identifier	User Specified
RUNDES	100 character run description (to appear at top of every page)	Blank
FILOVR	Input file overwrite switch. Switch that allows HERS input data file to be overwritten while processing. • 1 – Okay to overwrite • 0 – Do not overwrite, create a copy	0
FILDEL	End-state file deletion switch. Switch that allows HERS to delete file(s) describing the system(s) at the end of analysis. • 1 – Okay to delete • 0 – Do not delete	1

TABLE H-12 Continued

Control Input	Description	Default Value
FILIN	Binary section file name	name.HRS
DISTIN	Truck VMT distribution file name	name.DST
INTYEAR_FILENAME	Name of intermediate year file	Blank
LFP	Length of funding period	5
NFP	Number of funding periods	4
AADTTY	Type of AADT calculation to perform • 1 – original method • 2 – straight line method • 3 – proposed method	2
DO_INTYEAR_MIDDLE	Intermediate year selection control • 0 – use year specified in INTYEAR file • 1 – use middle of FP containing the specified year	0
INPUTLRS	Long run share of elasticity	–0.25
INPUTSRE	Short run elasticity	–0.40
DRATE	Discount rate, in percentage	7.0
INL	Intermediate number of lanes switch • 0 – When adding lanes, consider only increasing to the design number of lanes or not adding lanes at all • 1 – Also consider adding intermediate numbers of lanes	1
BACKLG	Backlog switch • 1 – Calculate backlog at beginning of the run • 0 – Don't calculate	0
MAXNTD	Maximum number of traffic control devices (stop signs and traffic signals) per mile	25.0
BBUDGET	Budget balance switch • 0 – normal run • 1 – partial balanced • 2 – fully balanced	0
REV_ITERATIONS	Number of revenue iterations to perform (between 1 and 5)	5
BASEXP	Base-year HERS-related capital expenditures ($M per year)	57,368
FRACVMT	Fraction of excess expenditures to be covered by VMT surcharge	1.00
FRACFTX	Fraction of excess expenditures to be covered by fuel tax surcharge	0.00

continued

TABLE H-12 Continued

Control Input	Description	Default Value
NHCIT	Multiplier for non-HERS capital improvement types	1.834
	Require reconstruction after number of years • 1 – Yes • 0 – No	0
	Reconstruction limit: flex/comp, rigid	30, 45
SURFLIMIT	Limit on consecutive resurfacing switch • 1 – limit • 0 – no limit	1
MAXSURF	Maximum number of consecutive resurfacings (if limit imposed above)	2
NEEDS	Full engineering needs switch • 1 – perform full engineering needs analysis • 0 – use objective specified below	1
BCRMIN	Minimum BCR	1.00
OBJCTV	Analytical objective • 1 – Fund constraint • 2 – Performance constraint • 3 – MinBCR at BCRMIN • 4 – Speed constraint • 5x – IRI Threshold (where “x” identifies UST) • 6x – V/C Threshold (where “x” identifies UST) • 7 – avg delay MCC	1
MCC	Maintain current conditions switch (MCC ignored if OBJCTV is not 2) • 1 – Maintain current conditions at minimum improvement cost • 0 – Use goal presented below	1
LASTIMP	When next improvement exceeds budget: • 0 – Split section and implement on part of section • 1 – Implement improvement and borrow from the next FP • 2 – Don’t implement and carry over funds to the next FP	0

TABLE H-12 Continued

Control Input	Description	Default Value
CSPEC	Constraint specification selector • 1 – By 9 functional classes • 2 – By principal arterial/other arterial and rural/urban • 3 – By principal arterial/other • 4 – By rural/urban • 5 – For the whole system at once	5
SCVALU	Table of fund/performance constraints • Objective 1: Funds available each funding period (millions of $) • Objective 2: Highway performance goals per vehicle-mile (or per mile, if goal is for maintenance cost only)—User Costs, Total Delay, or Average IRI • Objective 3: MinBCR at BCRMIN • Objective 4: Average speed BY VMT • Objective 5x: Maximum % of IRI (by VMT/miles) above IRI Threshold (USTx in DLTBLS) • Objective 6x: Maximum % of V/C (by VMT or miles) above V/C Threshold (USTx in DLTBLS) • Objective 7: Average delay by VMT	See Table 2a
CWT	Table of constraint weights (for OBJCTV type 2 only)	See Table 2b
MCUNIT	Maintenance cost units. Units of specified goal: • 1 – per VMT • 2 – per mile (MCUNIT = 2 valid for: OBJCTV = 5x or 6x; or 2 if all weights other than maintenance cost are 0)	1
BCRWT	Table of benefit-cost ratio weights	See Table 2c
OUTPUT	Table of output text page selections	See Table 2d
SCFACT	Tables of output scale factors (costs and VMT)	See Table 2e
	Vehicle Output for VMT • 0 – 3 Vehicle Classes • 1 – 7 Vehicle Types • 2 – Total Only	1
	Vehicle Output for Fuel Use • 0 – 3 Vehicle Classes • 1 – 7 Vehicle Types • 2 – Total Only	1
PPDUNITS	Peak period delay units • 1 – Million hours • 2 – Thousand hours	1

continued

TABLE H-12 Continued

Control Input	Description	Default Value
ANDPCTC	Allocate non-deficient pavement costs to capacity switch • 1 – Allocate • 0 – Allocate non-deficient costs to preservation	0
NPSEC	Number of sections to be processed between printings of "number of sections processed" message • 0 – No message	10,000
NSIMP	Number of improvements selected between printings of "number of selected improvements" message • 0 – No message	10,000
INMXLBCA	Maximum length of benefit-cost analysis period • 0 – Default (60)	20
CAPFAC_FP	Beginning FP for capacity adjustment factor • FP – to begin • 0 – to disable	0
CAPACFAC_IN	Capacity adjustment factor	1.250
IN_SECOUTPUT	Section output switch • 1 – Yes • 2 – No	1
CONGPRI_FP	Beginning FP for congestion pricing • FP – to begin • 999 – to disable	999
CONGPRI_THR	Congestion pricing V/C threshold (minimum V/C for toll)	0.80
CP_PEAK_IN	Congestion Pricing Peak Switch • 0 – All day toll • 1 – Peak only	0
TARGET_REVNU_IN	Target specific revenue switch • 0 – Do not use revenue targets • 1 – Use revenue targets	0
REVENUE_TARGETS	Table of specific revenue targets	FP 1: 135548.6 FP 2: 170297.1 FP 3: 213952.9 FP 4: 268799.9
MAX_PROC	Maximum number of processors to use • 1 – default • 9 or greater – all available	1

TABLE H-13 RUNSPEC.DAT—Table of Fund/Performance Constraints

Functional Classification	FP 1	FP 2	FP 3	FP 4	FP 5	FP 6	FP 7	FP 8	FP 9	FP 10
(1) By 9 functional classes										
Rural Interstate	a	a	a	a	a	a	a	a	a	a
Rural OPA	a	a	a	a	a	a	a	a	a	a
Rural MA	a	a	a	a	a	a	a	a	a	a
Rural Maj. Coll.	a	a	a	a	a	a	a	a	a	a
Urban Interstate	a	a	a	a	a	a	a	a	a	a
Urban Expwy	a	a	a	a	a	a	a	a	a	a
Urban OPA	a	a	a	a	a	a	a	a	a	a
Urban MA	a	a	a	a	a	a	a	a	a	a
Urban Collector	a	a	a	a	a	a	a	a	a	a
(2) By Princ. Art./Other and rural/urban										
Rural Princ. Art.	a	a	a	a	a	a	a	a	a	a
Urban Princ. Art	a	a	a	a	a	a	a	a	a	a
Rural Other	a	a	a	a	a	a	a	a	a	a
Urban Other	a	a	a	a	a	a	a	a	a	a
(3) By Princ. Art./Other										
Princ. Art.	a	a	a	a	a	a	a	a	a	a
Other	a	a	a	a	a	a	a	a	a	a
(4) By Rural/Urban										
Rural	a	a	a	a	a	a	a	a	a	a
Urban	a	a	a	a	a	a	a	a	a	a
(5) For the whole system										
	a	a	a	a	a	a	a	a	a	a

NOTE: a = User-specified goal (constraint) that can be different for each cell.

TABLE H-14 RUNSPEC.DAT—Table of Constraint Weights (for OBJCTV Type 2 Only)

	Rural				Urban				
	Interstate	OPA	MA	Major Collector	Interstate	Other Fwy/ Expy	OPA	MA	Collector
Operating Cost	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Travel Time Cost	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Property Damage	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Injury Cost	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Fatality Cost	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Number of Crashes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Injuries	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Fatalities	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maintenance Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Delay	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Average IRI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE H-15 RUNSPEC.DAT—Table of Benefit-Cost Ratio Weights

	Rural				Urban				
	Interstate	OPA	MA	Major Collector	Interstate	Other Fwy/ Expy	OPA	MA	Collector
Operating Cost Benefits	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Travel Time Benefits	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Property Damage Savings	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Injury Cost Savings	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Fatality Cost Savings	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Maintenance Benefits	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residual Value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Upstream CO_2 Damage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tailpipe CO_2 Damage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE H-16 RUNSPEC.DAT—Table of Output Text Page Selections

	Funding Period Results	Complete Run Results
Total initial cost of selected improvements	Requested	Requested
Lane-miles improved	Requested	Requested
Average BCR of selected improvements	Requested	Requested
Total benefits in the last year of period	Not Requested	Not Requested
Maintenance-cost savings in the last year of period	Not Requested	Not Requested
User benefits in the last year of period	Not Requested	Not Requested
Travel-time savings in the last year of period	Not Requested	Not Requested
Operating-cost savings in the last year of period	Not Requested	Not Requested
Safety benefits in the last year of period	Not Requested	Not Requested
Crashes avoided in the last year of period	Not Requested	Not Requested
Injuries avoided in the last year of period	Not Requested	Not Requested
Lives saved in the last year of period	Not Requested	Not Requested
VMT for improved sections in the last year of period	Not Requested	Not Requested
Miles improved	Requested	Not Requested
Capital requirement by IBCR range	Not Requested	Not Requested
Sample sections improved by IBCR range	Not Requested	Not Requested
Miles improved by IBCR range	Not Requested	Not Requested
Travel-time benefits to user-benefits ratios	Not Requested	Not Requested
Lane-miles added	Requested	Requested
Pollution damage savings in last year of period	Not Requested	Not Requested
Deficiencies as % of VMT	Not Requested	Not Requested
Deficiencies as % of MILES	Requested	Requested
Total cost of work zone delays	Not Requested	Not Requested

TABLE H-17 RUNSPEC.DAT—Tables of Output Scale Factors (Costs and VMT)

	Units
Costs	
Total initial cost of selected improvements	Millions of dollars
Total benefits in the last year of period	Millions of dollars
Maintenance-cost savings in the last year of period	Millions of dollars
User benefits in the last year of period	Millions of dollars
Travel-time benefits to user-benefits ratios	Millions of dollars
Operating-cost savings in the last year of period	Millions of dollars
Safety benefits in the last year of period	Millions of dollars
Capital requirement by IBCR range	Millions of dollars
Total cost of work zone delays	Millions of dollars
Pollution damage savings in the last year of period	Millions of dollars
VMT	
VMT for improved sections in the last year of period	Millions of vehicle-miles
VMT at the beginning/end of funding period, or the difference between VMT at the beginning and the end of funding period (basic report)	Millions of vehicle-miles

TABLE H-18 Improvement Costs

$ in Thousands per Lane-Mile			Reconstruction		Resurface			Add Lanes		Alignment	
2002 $			Lane Widening	Pavement	Lane Widening	Pavement	Shoulder Improvements	Normal Cost	High Cost	Normal Cost	High Cost
Rural	Interstate	Flat	1,182	772	669	274	51	1,519	2,106	2,106	2,106
		Rolling	1,325	792	770	292	84	1,647	2,665	2,665	2,665
		Mountainous	2,512	1,734	1,276	432	176	5,128	6,003	6,003	6,003
	Principal Arterials	Flat	923	618	558	220	34	1,217	1,742	1,742	1,742
		Rolling	1,042	635	634	245	57	1,303	2,103	2,103	2,103
		Mountainous	2,024	1,430	1,229	346	75	4,600	5,297	5,297	5,297
	Minor Arterials	Flat	844	543	520	195	32	1,106	1,553	1,553	1,553
		Rolling	1,019	601	647	210	59	1,268	2,000	2,000	2,000
		Mountainous	1,693	1,110	1,229	288	133	3,883	4,660	4,660	4,660
	Major Collectors	Flat	889	575	537	199	41	1,149	1,552	1,552	1,552
		Rolling	973	584	604	211	55	1,174	1,910	1,910	1,910
		Mountainous	1,476	914	879	288	85	2,486	3,247	3,247	3,247

Urban	Interstates/ Expressways	Small Urban	1,987	1,379	1,566	334	61	2,493	8,161	3,360	11,470
		Small Urbanized	2,136	1,388	1,620	395	81	2,724	8,950	4,529	15,461
		Large Urbanized	3,407	2,272	2,509	530	306	4,559	15,291	6,643	22,678
		Major Urbanized	6,814	4,544	4,869	878	612	9,118	38,022	13,286	50,826
	Principal Arterials	Small Urban	1,732	1,169	1,433	280	62	2,119	6,922	2,649	9,041
		Small Urbanized	1,853	1,183	1,498	331	83	2,296	7,528	3,268	11,155
		Large Urbanized	2,647	1,734	2,192	416	267	3,360	11,226	4,486	15,313
		Major Urbanized	5,294	3,468	4,384	672	534	6,720	26,049	8,972	38,838
	Arterials/ Collectors	Small Urban	1,276	883	1,084	205	45	1,565	5,069	1,911	6,524
		Small Urbanized	1,337	893	1,094	233	55	1,649	5,358	2,345	8,005
		Large Urbanized	1,800	1,194	1,496	286	150	2,286	7,590	3,052	10,417
		Major Urbanized	3,600	2,388	2,263	476	300	4,572	26,049	6,104	32,235

TABLE H-19 Deficiency Levels—Pavement Condition (IRI)

Pavement Condition (IRI)			UL	RL	DL	UST1	UST2	UST3
Rural	Interstate	Flat	250.0	190.0	65.0	120.0	95.0	170.0
		Rolling	250.0	190.0	65.0	120.0	95.0	170.0
		Mountainous	250.0	190.0	65.0	120.0	95.0	170.0
	Principal Arterials AADT > 6,000	Flat	250.0	190.0	65.0	120.0	95.0	170.0
		Rolling	250.0	190.0	65.0	120.0	95.0	170.0
		Mountainous	250.0	190.0	65.0	120.0	95.0	170.0
	Principal Arterials AADT < 6,000	Flat	300.0	190.0	65.0	120.0	95.0	170.0
		Rolling	300.0	190.0	65.0	120.0	95.0	170.0
		Mountainous	300.0	190.0	65.0	120.0	95.0	170.0
	Minor Arterials AADT > 2,000	Flat	350.0	225.0	80.0	120.0	95.0	170.0
		Rolling	350.0	225.0	80.0	120.0	95.0	170.0
		Mountainous	350.0	225.0	80.0	120.0	95.0	170.0
	Minor Arterials AADT < 2,000	Flat	350.0	225.0	80.0	120.0	95.0	170.0
		Rolling	350.0	225.0	80.0	120.0	95.0	170.0
		Mountainous	350.0	225.0	80.0	120.0	95.0	170.0
	Major Collectors AADT > 1,000	Flat	400.0	290.0	125.0	120.0	95.0	170.0
		Rolling	400.0	290.0	125.0	120.0	95.0	170.0
		Mountainous	400.0	290.0	125.0	120.0	95.0	170.0
	Major Collectors AADT > 400	Flat	450.0	290.0	125.0	120.0	95.0	170.0
		Rolling	450.0	290.0	125.0	120.0	95.0	170.0
		Mountainous	450.0	290.0	125.0	120.0	95.0	170.0
	Major Collectors AADT < 400	Flat	500.0	290.0	125.0	120.0	95.0	170.0
		Rolling	500.0	290.0	125.0	120.0	95.0	170.0
		Mountainous	500.0	290.0	125.0	120.0	95.0	170.0
Urban		Interstate	225.0	190.0	65.0	120.0	95.0	170.0
		Expressway	250.0	190.0	65.0	120.0	95.0	170.0
		Princ. Arterial	275.0	190.0	65.0	120.0	95.0	170.0
		Minor Arterial	400.0	225.0	80.0	120.0	95.0	170.0
		Collector	450.0	290.0	125.0	120.0	95.0	170.0

TABLE H-20 Deficiency Levels—Surface Type

Surface Type			UL	SDL	DL	UST1
Rural	Interstate	Flat	2-High	2-High	2-High	2-High
		Rolling	2-High	2-High	2-High	2-High
		Mountainous	2-High	2-High	2-High	2-High
	Principal Arterials AADT > 6,000	Flat	2-High	2-High	2-High	2-High
		Rolling	2-High	2-High	2-High	2-High
		Mountainous	2-High	2-High	2-High	2-High
	Principal Arterials AADT < 6,000	Flat	3-Intermediate	3-Intermediate	2-High	2-High
		Rolling	3-Intermediate	3-Intermediate	2-High	2-High
		Mountainous	3-Intermediate	3-Intermediate	2-High	2-High
	Minor Arterials AADT > 2,000	Flat	3-Intermediate	3-Intermediate	3-Intermediate	3-Intermediate
		Rolling	3-Intermediate	3-Intermediate	3-Intermediate	3-Intermediate
		Mountainous	3-Intermediate	3-Intermediate	3-Intermediate	3-Intermediate
	Minor Arterials AADT < 2,000	Flat	4-Low	4-Low	3-Intermediate	3-Intermediate
		Rolling	4-Low	4-Low	3-Intermediate	3-Intermediate
		Mountainous	4-Low	4-Low	3-Intermediate	3-Intermediate
	Major Collectors AADT > 1,000	Flat	4-Low	4-Low	3-Intermediate	3-Intermediate
		Rolling	4-Low	4-Low	3-Intermediate	3-Intermediate
		Mountainous	4-Low	4-Low	3-Intermediate	3-Intermediate
	Major Collectors AADT > 400	Flat	4-Low	4-Low	4-Low	4-Low
		Rolling	4-Low	4-Low	4-Low	4-Low
		Mountainous	4-Low	4-Low	4-Low	4-Low
	Major Collectors AADT < 400	Flat	5-Unpaved	5-Unpaved	5-Unpaved	5-Unpaved
		Rolling	5-Unpaved	5-Unpaved	5-Unpaved	5-Unpaved
		Mountainous	5-Unpaved	5-Unpaved	5-Unpaved	5-Unpaved

continued

TABLE H-20 Continued

Surface Type		UL	SDL	DL	UST1
Urban	Interstate	2-High	2-High	2-High	2-High
	Expressway	2-High	2-High	2-High	2-High
	Princ. Arterial	3-Intermediate	3-Intermediate	2-High	2-High
	Minor Arterial	4-Low	4-Low	3-Intermediate	3-Intermediate
	Collector	5-Unpaved	5-Unpaved	4-Low	4-Low

TABLE H-21 Deficiency Levels—V/C Ratio

V/C Ratio			UL	SDL	DL	WS	UST1	UST2
Rural	Interstate	Flat	0.90	0.85	0.60	0.70	0.70	0.80
		Rolling	0.95	0.90	0.70	0.80	0.70	0.80
		Mountainous	0.98	0.95	0.70	0.90	0.70	0.80
	Principal Arterials AADT > 6,000	Flat	0.90	0.85	0.60	0.70	0.70	0.80
		Rolling	0.95	0.90	0.70	0.80	0.70	0.80
		Mountainous	0.98	0.95	0.70	0.90	0.70	0.80
	Principal Arterials AADT < 6,000	Flat	0.90	0.85	0.60	0.70	0.70	0.80
		Rolling	0.95	0.90	0.70	0.80	0.70	0.80
		Mountainous	0.98	0.95	0.70	0.90	0.70	0.80
	Minor Arterials AADT > 2,000	Flat	0.90	0.85	0.60	0.70	0.70	0.80
		Rolling	0.95	0.90	0.70	0.80	0.70	0.80
		Mountainous	0.98	0.95	0.70	0.90	0.70	0.80
	Minor Arterials AADT < 2,000	Flat	0.90	0.85	0.60	0.70	0.70	0.80
		Rolling	0.95	0.90	0.70	0.80	0.70	0.80
		Mountainous	0.98	0.95	0.70	0.90	0.70	0.80
	Major Collectors AADT > 1,000	Flat	0.90	0.85	0.60	0.70	0.70	0.80
		Rolling	0.95	0.90	0.70	0.80	0.70	0.80
		Mountainous	0.98	0.95	0.70	0.90	0.70	0.80
	Major Collectors AADT > 400	Flat	1.00	1.00	0.70	0.95	0.70	0.80
		Rolling	1.00	1.00	0.70	0.95	0.70	0.80
		Mountainous	1.00	1.00	0.70	0.95	0.70	0.80
	Major Collectors AADT < 400	Flat	1.00	1.00	0.70	1.00	0.70	0.80
		Rolling	1.00	1.00	0.70	1.00	0.70	0.80
		Mountainous	1.00	1.00	0.70	1.00	0.70	0.80

TABLE H-21 Continued

Surface Type		UL	SDL	DL	WS	UST1	UST2
Urban	Interstate	0.98	0.95	0.70	0.90	0.70	0.80
	Expressway	0.98	0.95	0.70	0.90	0.70	0.80
	Princ. Arterial	0.98	0.95	0.70	0.90	0.70	0.80
	Minor Arterial	0.98	0.95	0.70	0.90	0.70	0.80
	Collector	0.98	0.95	0.70	0.90	0.70	0.80

TABLE H-22 Deficiency Levels—Lane Width

Lane Width (ft)			UL	SDL	DL	UST1
Rural	Interstate	Flat	11	11	12	12
		Rolling	11	11	12	12
		Mountainous	11	11	12	12
	Principal Arterials AADT > 6,000	Flat	10	11	12	12
		Rolling	10	11	12	12
		Mountainous	10	11	12	12
	Principal Arterials AADT < 6,000	Flat	10	11	12	12
		Rolling	10	11	12	12
		Mountainous	10	11	12	12
	Minor Arterials AADT > 2,000	Flat	8	9	12	12
		Rolling	8	9	12	12
		Mountainous	8	9	12	12
	Minor Arterials AADT < 2,000	Flat	8	9	12	12
		Rolling	8	9	12	12
		Mountainous	8	9	12	12
	Major Collectors AADT > 1,000	Flat	8	9	12	12
		Rolling	8	9	12	12
		Mountainous	8	9	12	12
	Major Collectors AADT > 400	Flat	8	8	11	11
		Rolling	8	8	11	11
		Mountainous	8	8	11	11
	Major Collectors AADT < 400	Flat	8	8	10	10
		Rolling	8	8	10	10
		Mountainous	8	8	10	10

continued

TABLE H-22 Continued

Lane Width (ft)		UL	SDL	DL	UST1
Urban	Interstate	11	11	12	12
	Expressway	10	11	12	12
	Princ. Arterial	9	10	12	12
	Minor Arterial	8	8	12	12
	Collector	8	8	12	12

TABLE H-23 Deficiency Levels—Right Shoulder Width

Right Shoulder Width (ft)			UL	SDL	DL	UST1
Rural	Interstate	Flat	6	7	10	10
		Rolling	6	7	9	9
		Mountainous	6	6	7	7
	Principal Arterials AADT > 6,000	Flat	6	7	9	9
		Rolling	6	7	9	9
		Mountainous	6	6	7	7
	Principal Arterials AADT < 6,000	Flat	6	7	9	9
		Rolling	6	7	9	9
		Mountainous	6	6	7	7
	Minor Arterials AADT > 2,000	Flat	6	6	7	7
		Rolling	6	6	7	7
		Mountainous	4	4	6	6
	Minor Arterials AADT < 2,000	Flat	4	5	7	7
		Rolling	4	5	7	7
		Mountainous	4	4	6	6
	Major Collectors AADT > 1,000	Flat	2	3	6	6
		Rolling	2	3	6	6
		Mountainous	2	3	6	6
	Major Collectors AADT > 400	Flat	0	0	4	4
		Rolling	0	0	4	4
		Mountainous	0	0	4	4
	Major Collectors AADT < 400	Flat	0	0	2	2
		Rolling	0	0	2	2
		Mountainous	0	0	2	2

TABLE H-23 Continued

Right Shoulder Width (ft)		UL	SDL	DL	UST1
Urban	Interstate	6	7	9	9
	Expressway	6	7	9	9
	Princ. Arterial	0	5	8	8
	Minor Arterial	0	5	8	8
	Collector	0	3	6	6

TABLE H-24 Deficiency Levels—Shoulder Type

Shoulder Type			UL	SDL	DL	UST1
Rural	Interstate	Flat	2-Stabilized	2-Stabilized	2-Stabilized	2-Stabilized
		Rolling	2-Stabilized	2-Stabilized	2-Stabilized	2-Stabilized
		Mountainous	2-Stabilized	2-Stabilized	2-Stabilized	2-Stabilized
	Principal Arterials AADT > 6,000	Flat	2-Stabilized	2-Stabilized	2-Stabilized	2-Stabilized
		Rolling	2-Stabilized	2-Stabilized	2-Stabilized	2-Stabilized
		Mountainous	2-Stabilized	2-Stabilized	2-Stabilized	2-Stabilized
	Principal Arterials AADT < 6,000	Flat	3-Earth	2-Stabilized	2-Stabilized	2-Stabilized
		Rolling	3-Earth	2-Stabilized	2-Stabilized	2-Stabilized
		Mountainous	3-Earth	2-Stabilized	2-Stabilized	2-Stabilized
	Minor Arterials AADT > 2,000	Flat	3-Earth	2-Stabilized	2-Stabilized	2-Stabilized
		Rolling	3-Earth	2-Stabilized	2-Stabilized	2-Stabilized
		Mountainous	3-Earth	2-Stabilized	2-Stabilized	2-Stabilized
	Minor Arterials AADT < 2,000	Flat	3-Earth	3-Earth	3-Earth	3-Earth
		Rolling	3-Earth	3-Earth	3-Earth	3-Earth
		Mountainous	3-Earth	3-Earth	3-Earth	3-Earth
	Major Collectors AADT > 1,000	Flat	3-Earth	3-Earth	3-Earth	3-Earth
		Rolling	3-Earth	3-Earth	3-Earth	3-Earth
		Mountainous	3-Earth	3-Earth	3-Earth	3-Earth
	Major Collectors AADT > 400	Flat	4-Curbed	3-Earth	3-Earth	3-Earth
		Rolling	4-Curbed	3-Earth	3-Earth	3-Earth
		Mountainous	4-Curbed	3-Earth	3-Earth	3-Earth
	Major Collectors AADT < 400	Flat	4-Curbed	3-Earth	3-Earth	3-Earth
		Rolling	4-Curbed	3-Earth	3-Earth	3-Earth
		Mountainous	4-Curbed	3-Earth	3-Earth	3-Earth

continued

TABLE H-24 Continued

Shoulder Type		UL	SDL	DL	UST1
Urban	Interstate	1-Surfaced	1-Surfaced	1-Surfaced	1-Surfaced
	Expressway	1-Surfaced	1-Surfaced	1-Surfaced	1-Surfaced
	Princ. Arterial	4-Curbed	2-Stabilized	2-Stabilized	2-Stabilized
	Minor Arterial	4-Curbed	3-Earth	3-Earth	3-Earth
	Collector	4-Curbed	3-Earth	3-Earth	3-Earth

TABLE H-25 Deficiency Levels—Horizontal Alignment

Horizontal Alignment			UL	SDL	DL
Rural	Interstate	Flat	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
		Rolling	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
		Mountainous	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
	Principal Arterials AADT > 6000	Flat	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
		Rolling	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
		Mountainous	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
	Principal Arterials AADT < 6000	Flat	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Rolling	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Mountainous	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
	Minor Arterials AADT > 2000	Flat	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Rolling	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Mountainous	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept

TABLE H-25 Continued

Horizontal Alignment			UL	SDL	DL
Rural	Minor Arterials AADT < 2000	Flat	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Rolling	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Mountainous	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
	Major Collectors AADT > 1000	Flat	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Rolling	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
		Mountainous	3-Some Red. Speed	2-All Curves Accept	2-All Curves Accept
	Major Collectors AADT > 400	Flat	4-Significant Curves	3-Some Red. Speed	2-All Curves Accept
		Rolling	4-Significant Curves	3-Some Red. Speed	2-All Curves Accept
		Mountainous	4-Significant Curves	3-Some Red. Speed	2-All Curves Accept
	Major Collectors AADT < 400	Flat	4-Significant Curves	3-Some Red. Speed	2-All Curves Accept
		Rolling	4-Significant Curves	3-Some Red. Speed	2-All Curves Accept
		Mountainous	4-Significant Curves	3-Some Red. Speed	2-All Curves Accept
Urban		Interstate	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
		Expressway	2-All Curves Accept	2-All Curves Accept	1-All Crv Appropriate
		Princ. Arterial	3-Some Red. Speed	2-All Curves Accept	1-All Crv Appropriate
		Minor Arterial	—	—	—
		Collector	—	—	—

TABLE H-26 Deficiency Levels—Vertical Alignment

Vertical Alignment			UL	SDL	DL
	Interstate	Flat	2-All Grades Accept	2-All Grades Accept	1-All Grd Appropriate
		Rolling	2-All Grades Accept	2-All Grades Accept	1-All Grd Appropriate
		Mountainous	2-All Grades Accept	2-All Grades Accept	1-All Grd Appropriate
	Principal Arterials AADT > 6,000	Flat	2-All Grades Accept	2-All Grades Accept	1-All Grd Appropriate
		Rolling	2-All Grades Accept	2-All Grades Accept	1-All Grd Appropriate
		Mountainous	2-All Grades Accept	2-All Grades Accept	1-All Grd Appropriate
	Principal Arterials AADT < 6,000	Flat	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Rolling	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Mountainous	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
Rural		Flat	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Rolling	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Mountainous	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
	Minor Arterials AADT < 2,000	Flat	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Rolling	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Mountainous	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
	Major Collectors AADT > 1,000	Flat	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Rolling	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept
		Mountainous	3-Some Red. Speed	2-All Grades Accept	2-All Grades Accept

TABLE H-26 Continued

Vertical Alignment			UL	SDL	DL
Rural	Major Collectors AADT > 400	Flat	4-Significant Grades	3-Some Red. Speed	2-All Grades Accept
		Rolling	4-Significant Grades	3-Some Red. Speed	2-All Grades Accept
		Mountainous	4-Significant Grades	3-Some Red. Speed	2-All Grades Accept
	Major Collectors AADT < 400	Flat	4-Significant Grades	3-Some Red. Speed	2-All Grades Accept
		Rolling	4-Significant Grades	3-Some Red. Speed	2-All Grades Accept
		Mountainous	4-Significant Grades	3-Some Red. Speed	2-All Grades Accept
Urban		Interstate	—	—	—
		Expressway	—	—	—
		Princ. Arterial	—	—	—
		Minor Arterial	—	—	—
		Collector	—	—	—

TABLE H-27 Design Standards

Design Standards			Surface Type	Lane Width	Right Shoulder Width	Curve	Grade	Median Width
Rural	Interstate	Flat	2-High	12	12	1-All Crv Appr	0.70	64
		Rolling	2-High	12	10	1-All Crv Appr	0.70	64
		Mountainous	2-High	12	8	3-Some Red. Speed	0.70	16
	Principal Arterials AADT > 6,000	Flat	2-High	12	10	1-All Crv Appr	0.70	40
		Rolling	2-High	12	10	1-All Crv Appr	0.70	40
		Mountainous	2-High	12	8	3-Some Red. Speed	0.70	16
	Principal Arterials AADT < 6,000	Flat	2-High	12	10	1-All Crv Appr	0.70	40
		Rolling	2-High	12	10	2-All Crv Accept	0.70	40
		Mountainous	2-High	12	8	3-Some Red. Speed	0.70	16
	Minor Arterials AADT > 2,000	Flat	2-High	12	8	1-All Crv Appr	0.70	40
		Rolling	2-High	12	8	2-All Crv Accept	0.70	40
		Mountainous	2-High	12	8	3-Some Red. Speed	0.70	16
	Minor Arterials AADT < 2,000	Flat	3-Interm	12	8	1-All Crv Appr	0.70	0
		Rolling	3-Interm	12	8	2-All Crv Accept	0.70	0
		Mountainous	3-Interm	12	6	3-Some Red. Speed	0.70	0
	Major Collectors AADT > 1,000	Flat	3-Interm	12	8	2-All Crv Accept	0.70	16
		Rolling	3-Interm	12	8	3-Some Red. Speed	0.70	16
		Mountainous	3-Interm	12	6	4-Significant Curves	0.70	16

TABLE H-27 Continued

Design Standards			Surface Type	Lane Width	Right Shoulder Width	Curve	Grade	Median Width
Rural	Major Collectors AADT > 400	Flat	4-Low	11	4	2-All Crv Accept	0.70	0
		Rolling	4-Low	11	4	3-Some Red. Speed	0.70	0
		Mountainous	4-Low	11	4	4-Significant Curves	0.70	0
	Major Collectors AADT < 400	Flat	4-Low	10	2	2-All Crv Accept	0.70	0
		Rolling	4-Low	10	2	3-Some Red. Speed	0.70	0
		Mountainous	4-Low	10	2	4-Significant Curves	0.70	0

Design Standards		Surface Type	Lane Width	Right Shoulder Width	Curve	Grade	Median Width
Urban	Interstate	2-High	12	10	3-Some Red. Speed	—	20
	Expressway	2-High	12	10	3-Some Red. Speed	—	20
	Princ. Arterial	2-High	12	9	3-Some Red. Speed	—	—
	Minor Arterial	2-High	12	9	—	—	—
	Collector	3-Interm	12	8	—	—	—

REFERENCES

Abbreviations

FHWA	Federal Highway Administration
FTA	Federal Transit Administration
U.S. DOT	U.S. Department of Transportation

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Appendix I

Case Studies

INTRODUCTION

Twenty-two case studies were analyzed to support the committee's deliberations regarding needs and strategy orientation. Not necessarily representative of all Interstate needs, the case studies are illustrative examples to support reasonable judgements regarding needs analysis. This synthesis reviews four key observation areas for the 22 project- or plan-based case studies:

1. Drivers and Deficiencies
2. Improvement Approaches
3. Forecasted Future Performance
4. Project Costs

CASE STUDY OVERVIEW

The case studies were identified using selection criteria that entailed geographical factors, user types, and improvement strategies (see Table I-1). Following the descriptions of groupings used to categorize the case studies, Table I-2 presents a brief description of the case study projects and plans as well as the rationale for their selection.

TABLE I-1 Selection Criteria for Case Studies

Geography	Users	Improvement Strategies
• Urban/Metro • Interurban • Rural	• Commercial/Freight • Passenger	• Preservation • Operations • Capacity • Technology

TABLE I-2 Brief Description of Case Study Projects, Plans

Projects/Plans	Description and Rationale
CA, Bay Area Express Lanes	The Bay Area is planning a 550-mile **network of Express Lanes** by 2035 to improve the operational efficiency. Metropolitan Transportation Commission (MTC) will operate 270 miles of the 550-mile Express Lanes network through conversion of 150 miles of existing carpool lanes to Express Lanes and addition of 120 miles of new lanes. This case study investigates highway improvements being undertaken in this area, and captures metrics relating to forecasted improvements in operational efficiency.
CA, I-8 CRCP, Imperial County	This case study involves 48 miles of pavement reconstruction with **continuously reinforced concrete pavement.** The pavement sections are designed to last up to 70 years with appropriate application of pavement preservation techniques.
CA, I-15 Integrated Corridor Management, San Diego	The 20-mile segment of I-15 between SR 78 and SR 52 is one of two demonstration sites for **Integrated Corridor Management** in the United States. This important inland commuting corridor between northern San Diego and Escondido and portion of the freight corridor between the Mexican border and Las Vegas incorporates the integration of numerous **ITS systems, transit, and reversible express lanes** to optimize the capacity and reliability during peak period use, incidents, and special events. A multi-agency collaborative effort to manage all available assets in a coordinated and integrated fashion has been shown to reduce person hours traveled and improve travel time reliability.
CA, I-710 Gerald Desmond Bridge, Long Beach	The Gerald Desmond Bridge carries I-710 serving as a major access point to the Port of Long Beach from downtown Long Beach, California, and surrounding communities. The traffic LOS on the bridge is forecast to operate at LOS F in year 2030, while the existing bridge was physically deteriorated. The $1.5 billion replacement project will build six-lane, cable-stayed design bridge, with a 205-foot clearance to allow the newest generation of cargo ships to enter the Port. The bridge will include emergency lanes on the inner and outer shoulders, as well as a bicycle/pedestrian path. The case study focuses on the bridge replacement project as well as the long-life concepts used for bridge design. The bridge will be designed for 100 years using the emerging **service life design** concepts with a special emphasis on **material durability** in a harsh marine environment.

TABLE I-2 Continued

Projects/Plans	Description and Rationale
CO, SMART 25 Managed Motorways, Denver	This $7 million **Managed Motorways** demonstration project will add sensors to the lanes on the northbound side of 13 miles of I-25 south of downtown Denver. This stretch has 17 points of access or egress, including the interchange with E-470. Typically, the northbound lanes operate at around 60 mph until 7:15 AM, but then break down to 30 mph as traffic volumes grow during the morning rush hour. Working in collaboration with VicRoads (the transportation department in Victoria, Australia, where Melbourne is located) Colorado Department of Transportation (CDOT) is installing a network of sensors in the corridor that will send traffic data (number of cars in a lane and travel speeds) to VicRoads, which will analyze the information in real time and send directions back to upgraded ramp meters in this section of the highway, telling them how many cars to allow on to the highway. This system will smooth traffic flow, filling gaps, and avoiding pockets of saturation. It is estimated to deliver the additional capacity equivalent to a new travel lane. The SMART 25 demonstration is expected to go live in the spring of 2018. If it functions as expected, CDOT is likely to expand the system. Other states including Utah, Georgia, and North Carolina are following the pilot closely and may follow suit as well.
FL, Southeast Florida Express Lanes Network: 595 Express	This comprehensive express lanes network includes several vital **express lane systems** currently in operation, construction, or planning/design in Miami-Dade, Broward, and Palm Beach Counties. The systems are part of Florida's Strategic Intermodal System, a designated network of transportation facilities important to the state's economy and mobility that receives priority consideration for funding. Population growth, economic competitiveness, and climate resilience are driving these improvements.
GA, I-85 Kia Boulevard Interchange, West Point, Troup County	This case study focuses on the construction of a **new diamond shaped interchange** in Troup County in west central Georgia. This interchange will provide safe and efficient access an adjacent Kia automobile manufacturing plant and training facility. The new facility was expected to generate thousands of daily automobile and truck trips to and from the site vicinity enroute I-85. The interchange was opened to traffic in 2008.
IA, I-80/I-29, Divided Dual Freeway, Council Bluffs	The case study is a typical Interstate modernization project in a mid-sized urban area to address future transportation needs. The project involves **major widening** and interchange improvements to construct a dual, divided freeway with three express lanes to through I-80 traffic and two local lanes to I-80/I-29 traffic.

continued

TABLE I-2 Continued

Projects/Plans	Description and Rationale
KY-IN, I-65 Ohio River Bridges, Louisville	The primary intent of this project is to address inadequate **cross-river system linkage opportunities** and relating **congestion** impacts on the Kennedy bridge and interchange, given that no viable alternatives are available for at least 50 miles on either sides along the Ohio River. This project improves cross-river mobility through the construction of a new bridge, interchange reconfiguration, and freeway rerouting through a by-pass roadway.
MN, I-535 Blatnik Bridge, Duluth	This case study focuses on the application of life-cycle performance modeling and cost analysis in developing an **optimized life-cycle plan** for future bridge maintenance, rehabilitation, and replacement decisions. The case study documents existing bridge conditions, future performance risks, evaluation of remaining life, development of feasible alternatives of preservation strategies, and recommendation of an optimized life-cycle activity plan and associated investments necessary to maintain the bridge for the next 15 to 40 years.
NV, Future I-11-Phase 1 and Phase 2, Boulder City	This project addresses the concerns of lack of **contiguous interstate connectivity** for interurban passenger and freight travel between Phoenix and Las Vegas. Upon completion, this project will provide connectivity between I-15 through I-515 spur and Arizona State Line. This route is one of the congressionally designated high-priority corridor (#26) for its importance to the nation's economy, defense, and mobility.
NY, I-590 Winton Interchange, Rochester	This case study involves an **interchange reconfiguration** project in Rochester, New York. This $5.6 million project, which was completed in 2013, upgraded a traditional diamond interchange to a diverging diamond interchange. Prior to reconfiguration, the interchange experienced high crash rates and significant delays during peak hours.
OH, I-75 Reconstruction, Allen County	I-75 is one of the nation's most heavily traveled truck freight corridors. Deteriorating bridge and pavement conditions, narrow shoulders, and other design deficiencies were identified on this section of I-75 near Lima in Allen County, Ohio. These deficiencies lead to increased maintenance costs, increased risk of crashes, and increased delay during crashes. This three-project **reconstruction** corrected design deficiencies, reconfigured interchanges, increased the overhead clearance of overpasses, and constructed an auxiliary lane between two interchanges.

TABLE I-2 Continued

Projects/Plans	Description and Rationale
PA, I-70 New Stanton Interchange	Two substandard interchanges on the I-70 corridor in New Stanton, Pennsylvania, were consolidated into a single modern interchange with a **double roundabout** configuration. This interchange, which is located about 1 mile away from the I-76/I-70 system interchange, was constructed in response to higher crash rates, poor LOS at ramps, and outdated design standards. The $53.7 million project included a new, relocated interchange with double roundabouts at ramps, a park-and-ride facility, pedestrian access, and replacement of a structurally deficient bridge deck. The concept of roundabouts was preferred to improve safety and operational performance.
RI, Iway I-195 Relocation, Providence	The **reconstruction** of I-195 through Providence was an opportunity to correct numerous design deficiencies and replace deteriorated bridges combined with the **reclamation of 20 acres of downtown, riverfront property for redevelopment.** The project reconstructed and relocated a 1.6-mile segment of I-195 and an adjacent 0.8-mile section of I-95. The project included 14 new bridges with a 1,200-foot, 8-lane mainline bridge over the Providence River, 25 lane-miles of new Interstate, a new interchange with I-95, 5 miles of new city streets, and 4,100 feet of new pedestrian riverwalks. The redesigned highway segments provide improved operational characteristics and safety. The freed-up parcels are being redeveloped as an "innovation and design" district.
TX, I-35A Waco Project 5A	Increased truck traffic along the I-35 corridor coupled with regional population growth in Texas created travel demand that exceeded capacity. The existing I-35 facility through Central Texas is an essential element of the local and regional transportation system. The purpose of the project was to meet local and regional travel demands by **increasing capacity** and upgrading the transportation infrastructure to meet current FHWA and Texas DOT design standards for interstates, bridges, and frontage roads, thereby improving the safety of travelers along I-35. The project included widening 13.4 miles of I-35 from 4 to 6 lanes, upgrading on- and off-ramps, converting frontage roads to one-way, and converting underpasses to overpasses.
TX, I-69 Upgrade of US 77	This proposed project is **upgrading** the existing 8-mile four-lane divided facility to **Interstate standards.** The existing facility has many at-grade unsignalized intersections to provide access to local roads and ranch gates. The proposed project is reconstructing the existing roadway with grade-separated intersections and frontage roads to maintain access to local traffic, 70-mile free flow speed, and ensure highway safety. This route is a part of a congressionally designated **High-Priority Corridor** (#18) to provide **new connections** for freight travel between Rio Grande Valley and Michigan/Canadian border, facilitate **freight oriented multimodal integration** with rail, air, and inland water transportation at Memphis, and improve interstate connectivity of many towns in western Tennessee.

continued

TABLE I-2 Continued

Projects/Plans	Description and Rationale
TX, US 75 Integrated Corridor Management, Dallas	The 28-mile stretch of US 75 (which effectively operates as an interstate) between Plano and downtown Dallas was selected as one of two **Integrated Corridor Management** demonstration sites in the United States. The corridor includes a minimum of 8 GP lanes, concurrent flow HOV lanes, frontage roads, parallel arterials, and a parallel light rail line served by park-and-ride lots. Multiagency coordination and a decision support system with pre-programed response plans is the heart of a system that alerts drivers to cascading **alternative routes and modes** in the event of an incident on US 75. Travelers can be directed to the frontage roads, a parallel arterial, or transit depending on the location and severity of the incident. Demonstration results indicate a reduction in person hours traveled and improved travel time reliability.
UT, I-15 Corridor	The 400-mile section of I-15 through Utah is a critical corridor from two distinct perspectives. In one sense, I-15 represents a critical north-south corridor through a predominantly rural state with significant implications for rural community access and mobility, interstate and intrastate freight movement, and access to recreation and energy production sites important to the state's economy. The corridor also passes through the geographically constrained Wasatch Front that encompasses the Salt Lake City-Provo-Orem metropolitan region, home to more than 80 percent of the state's population, where I-15 serves as a major interurban corridor. Therefore, planning for future improvements includes **both traditional rural interstate widening** and interchange projects as well as **innovative mobility improvements along its urban stretch** where further widening is limited.
VA, I-66 Outside the Beltway, Fairfax	The I-66 project, which was procured recently using public–private partnership service delivery model, intends to address the existing problems, primarily relating to inadequate capacity, localized choke points, and unreliable travel times, on this 22-mile corridor, as well as to meet the future person-through-put demands using **diverse travel mode choices.** This project will add 22 miles of managed lanes to relieve congestion, improve safety, enhance travel model choices using bus and rail transit integration, park-and-ride lots, reconstructing roadways and interchanges. This commuter-heavy corridor exemplifies an **integrated multimodal approach to mobility** to address growing capacity needs in metropolitan areas.

TABLE I-2 Continued

Projects/Plans	Description and Rationale
WA, I-405 Corridor, Seattle	Originally intended as a bypass route, the 30-mile corridor of I-405 in east suburban Seattle is Washington State's second most heavily traveled expressway. High growth in population, employment, and traffic congestion characterize the largely suburban region that surrounds the corridor. The corridor exemplifies the **multi-pronged approach to mobility,** with multimodal enhancements, necessary to address corridor capacity deficiencies in urban regions. Widening for Managed Lanes, HOV lane conversion, a direct connector to existing express lanes, interchange enhancements, peak-period shoulder use, and improved routing and frequency of enhanced bus and BRT service are all incorporated into a multi-project, phased corridor plan supported with sizable non-federal revenue generation.
WY, I-80 Connected Vehicle Pilot	I-80 across southern Wyoming is a significant Interstate freight corridor (and intrastate route) with 30–55 percent of traffic being trucks, rising to 70 percent seasonally. The corridor experiences challenging weather conditions impacting safety and the economy through road closures and incidents. Gaps exist in the ability to detect road and weather conditions and to communicate traveler information and influence driver decisions. To help address these deficiencies, Wyoming DOT is engaged with U.S. DOT to **implement a CV pilot** along the corridor that will (1) improve road condition reporting by gathering data from equipped snow plows and trucks, (2) add in-vehicle dissemination of advisories to support speed management, detours, parking, and presence of maintenance and emergency vehicles, (3) provide current and forecasted road conditions to fleet managers, and (4) develop local V2V communication of road condition and posted speeds. To accomplish this, the pilot will **deploy and evaluate several CV technologies:** 75 roadside units to broadcast messages via DSRC, 400 onboard units (fleet vehicles, commercial trucks) to collect and transmit data, V2V and V2I applications to enable communication with drivers for alerts and advisories regarding various road conditions, and improvements in WYDOT's traffic management and traveler information practices by using data collected from connected vehicles.

The case studies were grouped into four "case study categories" based on the geographical, user characteristics, and improvement strategies.

- **Urban Corridors/Regions:** This category of case studies explores the needs of Interstates in some of the top metropolitan areas of the nation. Primarily catering to commuter traffic, the freeways in these densely populated urban areas serve as arterials to many residential clusters and employment centers that sprawl along the corridor.

  While most segments of the freeways are fast approaching capacity levels resulting in increased congestion, safety risks, and travel time reliability issues, roadway expansion strategies, such as new connections and lane additions, are not often viewed as sustainable and effective, as a steady growth in travel demand continues to outpace any added roadway capacity. Furthermore, capacity expansion in these areas is often constrained by local geographical factors and high right-of-way costs. The highway agencies generally opt for a combination of operational strategies, such as the use of managed lanes, with or without limited capacity expansion, to manage demand and create additional efficiencies in traffic flow.

  The case study projects and plans included in this category are primarily the application or demonstration of advanced traffic management strategies, combined in some cases with reconstruction or capacity expansion:

  i. I-66 Outside the Beltway in Northern Virginia
  ii. I-405 Corridor Express Lanes in Washington State
  iii. Network of express lanes in Southeast Florida
  iv. Express lane planning in the San Francisco Bay Area
  v. I-15 Corridor through the Wasatch Front metropolitan region in Utah
  vi. Integrated Corridor Management along I-15 in San Diego
  vii. Integrated Corridor Management along US 75 in Dallas
  viii. Managed Motorway demonstration along I-25 in Denver
  ix. Relocation of I-195 in Providence, Rhode Island

- **Interurban/Freight Corridors Traversing Urban Centers:** The case study projects include multi-state corridors in mid-sized cities. When Interstate corridors carrying freight and interurban traffic traverse through urban centers, congestion chokepoints may frequently occur due to localized surge in traffic demand from local traffic. These problems are often exasperated by physical bottlenecks (e.g., bridges for cross-river mobility) and convergence of multiple high-volume roadways (e.g., more than one Interstate or U.S. route). Highway agencies may find feasible opportunities for capacity addition to manage congestion.

The case study projects identified for this category include (i) I-65 Ohio River Bridges in Louisville, Kentucky, (ii) I-80/I-29 Dual Divided Freeway in Council Bluffs, Iowa, (iii) Future I-11 Boulder City Bypass in Clark County, Nevada, and (iv) I-35A Waco Project 5A in Waco, Texas. The first two case studies investigate the levels of service of freeway segments and interchanges of Interstates that pass through the cities of Louisville and Council Bluffs, which were originally constructed in the 1960s, while the third case study investigates the option of a new "bypass" connection that is being built with an intention of avoiding a freeway cutting through the commercial strip of Boulder City, and the last case study examines the more straightforward approach of adding capacity and upgrading infrastructure to meet current standards.

- **Interchanges:** This category can apply to all three identified geographies and comprises a system interchange (freeway-to-freeway, or all free-flow movements from one roadway to the other, and vice versa) or a service interchange (one or more movements must stop via stop sign or signal or yield to movements on the other roadway). Interchange improvements are considered operational in nature and often serve to improve mobility, safety, and accessibility. Three case studies investigate service interchanges: (i) diverging diamond interchange upgrade at I-590 and Winton Road outside Rochester, New York, (ii) new interchange along I-85 providing access to a new Kia Motors Manufacturing plant in Troup County, Georgia, and (iii) double roundabout interchange upgrade along I-70 in New Stanton, Pennsylvania. Several system interchanges of varying complexity are included as components of other case studies.
- **Rural Corridors:** This category includes rural segments of Interstate roadways. Four case studies were included: (i) the rural component of the I-15 corridor in Utah, (ii) the upgrade of US 77 in Texas to Interstate design standards for future I-69E, (iii) the reconstruction of I-75 near Lima in Allen County, Ohio, and (iv) the demonstration of connected vehicle (CV) infrastructure and applications along I-80 in Wyoming.

  The rural component of the I-15 corridor intends to capture traditional deficiencies in rural segments, common capacity and operational improvement types that are being undertaken, and associated costs. The US 77 case study looks at the adequacy of geometric design elements involved in the upgrade of existing roadways to Interstate design standards in rural areas. I-75 is one of the nation's most heavily traveled truck freight corridors and required reconstruction to correct design deficiencies and reduce the maintenance burden. Wyoming's I-80 experiences safety and economic impacts from largely weather-related incidents along this critical freight corridor. It seeks to decrease the occurrence and severity of these impacts through connected vehicle technologies deployed on a demonstration basis.

- **Roadway Assets:** This category can apply to all three identified geographies and includes projects that primarily involve preservation (i.e., rehabilitation, partial or total reconstruction) of roadway assets, particularly pavements and bridges, within the existing footprint. These projects may utilize future technologies, such as long-lasting materials and accelerated construction techniques, long-life design concepts, and asset resilience considerations. The case study projects included in this category are (i) the reconstruction of I-8 pavements in Imperial County, California, using Continuously Reinforced Concrete Pavement, (ii) the replacement of the I-710 Gerald Desmond Bridge in Long Beach, California, and (iii) an optimized life-cycle plan for future bridge maintenance, rehabilitation, and replacement decisions applied to the I-535 Blatnik Bridge in Duluth, Minnesota.

CASE STUDY GOALS

The specific goals of the case studies are to gain valuable insights relating to the following aspects of modeling:

- What improvement types are being planned or implemented at project level to meet future needs? Why were they undertaken? What are the drivers that influence those deficiencies? What aspects of condition or performance did they address? What is the forecasted growth in vehicle-miles traveled (VMT) at the project level based on the drivers considered?
- What is the general philosophy in identifying Interstate improvements relating to capital highway improvements versus non-highway improvements? How are various improvement types bundled?
- What additional strategies are highway agencies incorporating to address safety, land use, quality of life, and environmental considerations? How are these strategies influencing the performance related to these considerations?
- How well are the improvement types addressing the needs of passenger users, commercial users, and non-users (community) in

either qualitative or quantitative terms? The performance metrics that are being evaluated include, but not limited to, metrics relating to travel demand, travel mode, mobility, and safety.

- Update unit costs for traditional construction (e.g., capital improvements).
- What is the actual, expected, or projected improvement in performance/service life with the adoption of modern technology, construction techniques, materials, and features?
- What is the forecasted growth in travel demand at regional or corridor level, and what is the expected performance under an approved plan? (for plans only)
- Were strategies used as a surrogate to direct Interstate improvements because of local goals (e.g., densification, alternate modes, and demand management)? What is the effect of these surrogate improvements on future Interstate? (for plans only)
- Are highway disinvestment or decommissioning strategies being planned or implemented on Interstate roadways? If yes, what are the consequences on system performance, such as percentage change in pavement condition, bridge condition, weight restrictions, speed, control access, vehicle miles of travel, and vehicle hours of travel?

DRIVERS AND DEFICIENCIES

Demographic Growth

Demographic growth is the most common driver behind the decision to invest in the 22 Interstate study highway case study improvement projects. Population growth is explicitly stated as a key driver for 16 of the 22 case studies, including all five of the urban commuter traffic projects, both integrated corridor management projects, and the SMART 25 demonstration in Denver. An additional three projects—the I-590 Winton Interchange near Rochester, New York, I-75 Reconstruction in Ohio, and the I-35 widening in Waco, Texas—cite modest population growth or the need to provide capacity for future traffic as a driver to invest in Interstate improvement projects. The project documentation also cites long-term population growth rates over 25- to 40-year periods as an additional demographic driver for the case study projects, with expansion rates ranging between 22 and 72 percent. Growth in employment is cited as a driver for 11 of the case study projects. Growth in the number of households is also cited as a driver behind the I-66, Ohio River Bridges, and Future I-11 case studies.

Several of the case study projects have additional region-specific drivers that complement population and employment growth in densifying urban and metropolitan areas. For example, the lack of affordable housing and the need to meet greenhouse gas–reduction targets are both cited as drivers behind the San Francisco Bay Area Express Lanes network. The documentation for the I-15 Integrated Corridor Management project in San Diego also cites housing growth as a driver, especially in less expensive locations in southeast Riverside County, which increases commuter volumes in the corridor. While it may be implicit as a driver in other locations, enhancing local quality of life is also cited as need for the 595 Express project in Broward County, Florida.

In addition to growth in employment and population, the related growth in VMT and daily traffic delay are cited as drivers for the US 75 Integrated Corridor Management project in the Dallas-Fort Worth Metroplex.

Accessibility and Mobility

The need to improve accessibility and mobility is cited as an important driver behind nine of the case study improvement projects. The specific accessibility needs vary among the case study projects. For example, with the 595 Express project, two accessibility related drivers are cited: the need to eliminate congestion on the sole east/west Interstate corridor in Broward County and the need to support goods movement to and from Port Everglades and Fort Lauderdale Hollywood International Airport. The corridor is also designated as part of the Florida DOT's Strategic Intermodal System (SIS), which has significant funding available for capital improvements. Supporting goods movement and trucking is also an important driver for the I-15 corridor in Utah, where statewide truck freight is expected to grow 55 percent by weight between 2012 and 2040 and 111 percent by value. The I-35 widening from Waco to West in Texas is driven by the need to accommodate international and intracity truck traffic, which accounts for 29 percent of AADT. These projects address bottlenecks on important freight corridors as they intersect urban centers. High truck volumes (30–55 percent, and up to 70 percent seasonally) are also cited as a need for the I-80 Connected Vehicle Pilot in Wyoming.

One of the primary needs for the I-710 Gerald Desmond Bride project in Long Beach, California, is providing adequate roadway capacity to accommodate traffic moving to and from and between the port of Long Beach and the Port of Los Angeles. An additional accessibility driver is the need to raise the vertical clearance of the bridge to provide adequate clearance for larger post-Panamax cargo vessels using the port. This is important to the future competitiveness of the largest port in the United States. In Denver, one of the drivers behind the SMART 25 demonstration project is the desire to restore the mobility benefits of the $1.6 billion T-REX project, which was completed in 2006 and added highway and rail capacity in the corridor.

Improving accessibility and mobility are also drivers on projects in more rural settings, including the Future I-11 in Nevada, the upgrade of US

77 south of Corpus Christi, Texas, and the I-85 Kia Boulevard Interchange in Georgia. The Future I-11 project will expand existing rural capacity, while the US 77 will replace a four-lane highway in kind with a four-lane Interstate facility. Both of these projects are on high-priority international freight corridors providing Interstate connections between Canada and Mexico. These projects will also provide new Interstate highway connections between important domestic locations, Las Vegas and Phoenix in the case of Future I-11, and Houston and Brownsville, Texas, with the US 77 upgrade. The US 77 project is also intended to improve system continuity on an existing rural highway with speed limits that vary between 30 and 70 miles per hour. The I-85 Kia Boulevard Interchange will provide enhanced access to a Kia Motors manufacturing plant and by so-doing improve economic development opportunities and employment growth.

The Ohio River Bridges project addresses the deficiency of adequate cross-river capacity between southern Indiana and Louisville, Kentucky. It enhances cross-river mobility by adding a second bridge in the I-65 corridor and with the construction of a new crossing and greenfield connecting highways to the east. The need for expanded hurricane evacuation routes is cited as an additional accessibility driver for projects providing access to coastal communities, including the 595 Express and US 77.

Safety and Operational Improvements

Improving safety conditions is a common driver among a majority of the case study projects. In certain cases, safety is cited directly as a project driver. In others, specific factors that contribute to deteriorating safety are cited as deficiencies that need to be remediated. For example, the I-66 project is intended to address several deficiencies influencing safety, such as travel demand exceeding capacity, severely congested conditions during peak hours, deficient geometric features, and unreliable travel conditions. Similarly, the I-405 Express Toll Lanes address inadequate capacity, delays and congestion, and weaving friction at interchanges. The 595 Express project addresses similar issues including speed differentials between through traffic and vehicles exiting the highway, weaving frictions, and a lack of auxiliary lanes near interchanges. The Ohio River Bridges address interchanges and bridge congestion on I-65, which is also an important trucking corridor.

Although safety issues are not mentioned directly with the I-80/I-29 Dual Divided Freeway project in Council Bluffs, Iowa, its primary drivers are safety-related. This project will improve the capacity and configuration of two heavily traveled interchanges in order to separate local and through traffic, as well as traffic on I-80 and I-29. The project will address several related issues, including geometric deficiencies, weaving friction, and poor volume-to-capacity ratios. This is a common theme among projects involving the replacement or upgrade of older Interstate facilities that do not comply with current design standards. This includes the reconstruction of I-75 in rural Allen County, Ohio, the I-195 Iway project in Providence, Rhode Island, the I-70 New Stanton Interchange in Pennsylvania, and the widening and reconstruction of I-35 from Waco to West in Texas.

Safety is a primary driver of both case study projects involving the upgrade of local highways to full Interstate system standards. The future I-11 project in Boulder City, Nevada, will address severe congestion on US 93, which operates at level of service (LOS) F during peak periods with speeds between 30 and 40 miles per hour and a high volume-to-capacity ratio. This project also features a 15.5-mile bypass route around Boulder City that will eliminate un-signalized intersections, as well as direct access from the highway to local businesses and homes.

Safety is cited as the primary driver of the upgrade of US 77 to future I-69 between Kingsville and Driscoll, Texas. While the existing highway is not congested, the upgrade project will remove at-grade intersections with US 77, reduce high crash rates on the highway, and safely accommodate the high preponderance of truck traffic and future growth in trucking.

Structural Integrity

The structural integrity of older projects is one of the key deficiencies triggering the need for replacement and rehabilitation projects, particularly for bridges. The need for a structurally sound and seismically resistant bridge is the primary driver of the I-710 Gerald Desmond Bridge replacement. In Duluth, the need to improve the structural adequacy was also the primary driver for the I-535 Blatnik Bridge project. Similarly, the reconstruction of I-75 in Ohio was driven by the need to reconstruct pavements and bridges in the corridor.

Managed Lane Drivers and Deficiencies

The case studies include two projects intended to remediate deficiencies relating to managed lanes. The I-66 project will address the issue of a lack of travel alternatives to single occupancy vehicle (SOV) trips in the corridor. This managed lane project will encourage ride sharing, as well as the provision of improved transit options. The I-405 Express Toll Lane project addresses the fact that the HOV lanes it replaced did not meet federal speed targets, raising the possibility that federal maintenance funds could have been revoked by the Federal Highway Administration (FHWA). FHWA considers HOV facilities to be degraded if they fail to maintain a minimum average operating speed of 45 miles per hour 90 percent of the time over a consecutive 180-day period during morning or evening weekday peak hour periods (or both for a reversible facility).

Other Drivers and Deficiencies

Constraints to highway widening is cited as a deficiency with the I-15 project in Utah, as are the impacts of highway widenings with the Bay Area Express Lane Network. As a result, to the maximum extent possible, the Bay Area express lane network will be created by converting existing HOV facilities to high occupancy toll (HOT) operation. Existing highways will only be widened where gaps exist between current HOV facilities. However, due to the impacts of highway widenings, not all gaps will be filled.

The I-80/I-29 Dual Divided Freeway project will address the poor condition of the current highways, which is cited as a deficiency, while the I-8 pavement reconstruction project in Imperial County, California, is driven by the fact that the pavement is nearing the end of its useful life on this interurban and freight corridor. In Utah, the I-15 project is intended to improve a number of current and projected deficiencies, including reliable person throughput, access, air quality, economic outcomes, household transportation costs, and modal balance in the corridor.

In Rhode Island the desire to implement the City of Providence Old Harbor Plan was an important driver behind the reconstruction and relocation of I-195. This opened 35 acres of waterfront property to development, thereby reuniting Downtown Providence with the Jewelry District, improving waterfront access and transportation, expanding parkland, and providing economic development opportunities.

Other drivers for the I-80 Connected Vehicle Pilot include challenging weather conditions such as wind and snow. A key driver for the 13.4-mile I-35 widening project from Waco to West is that it is part of a larger high-profile program to widen 96 miles of I-35.

IMPROVEMENT APPROACHES

Key observations on improvement approaches can be made by the implied geographies and physical contexts of the case study categories.

Urban Corridors/Regions

Operations More Than Capacity

Large urban regions are often characterized by mature Interstate (and other freeway) networks, with constrained geographies, little unused right-of-way, and expensive construction environments limiting the ability to implement capacity expansion solutions. Capacity-related deficiencies are increasingly being addressed with operational solutions centered around demand management strategies (see Table I-3). New capacity is not impossible, but a balanced approach must be struck, as demonstrated with express toll lane

TABLE I-3 Predominant Improvement Strategies in Urban Corridor/Region Case Studies

Selected Urban Corridor/Region Case Studies	Operational Improvement Approaches
I-66 Outside the Beltway	Managed lanes—HOV 3+ and buses travel free Conversion of 1 GP lane to 1 ML Conversion of existing HOV 2+ to HOV 3+ New and improved bus routes New transit stations and 3 park-and-ride facilities with 4,000 parking spaces (to promote transit and ride-sharing) Access points to transit stations and park-and-ride facilities Geometric and safety improvements, including auxiliary lanes between interchanges
I-405 Express Toll Lanes	Demand management using managed lanes (pricing—ETL) Transit shoulders Peak-use shoulder (subsequent improvement) Multimodal enhancements—BRT line and stations, expanded local bus service, increased vanpools, park-and-ride spaces (planned for future)
San Francisco Bay Area Express Lanes	Express lanes—HOV conversion, GP lane conversion, lane additions
I-15 Integrated Corridor Management	Integrated Corridor Management—integrates managed lanes (express toll lanes), ramp meters, ITS, incident response improvement, traffic signal coordination, multimodal enhancements (bus rapid transit, improved traveler information)
US 75 Integrated Corridor Management	Integrated Corridor Management—integrates a managed lane (HOV), ITS, incident response improvement, traffic signal coordination, multimodal enhancements (light rail transit/parking, improved traveler information)
SMART 25 Managed Motorways	Managed motorways—advanced system of ramp meters and traffic sensor technology to reduce congestion by optimizing access and density of traffic

(ETL) additions that include HOV/general purpose (GP) lane conversions and new tolled capacity (I-66 Outside the Beltway, I-405 ETL, Bay Area Express Lanes). These selected projects indicate a rough cost for HOV-to-ETL conversion of $3 million per mile and range for new ETL construction of $7.5 million to more than $40 million per mile (see Table I-11). The lower end of new ETL construction corresponds to fewer urban, undeveloped regions, while the upper end includes ancillary asset reconstruction (two bridges). Costs also vary depending on the need for right-of-way acquisition and the by the number of ramps and interchanges included.

Advanced corridor solutions are also emerging that seek to holistically manage a complete corridor from a multimodal perspective (integrated corridor management) and that tightly control an interstate corridor's capacity in real time through sophisticated algorithms (managed motorways). These solutions will be necessary to maximize person throughput and the efficiency of a constrained physical corridor.

In some, likely infrequent cases, the opportunity to recapture valuable urban footprint—socially and economically—may present itself during urban Interstate reconstruction activities, which as with operational solutions, may be combined with modest capacity enhancements. One case study examines this scenario, as summarized in Table I-4.

As discussed in the previous section, strong growth in population and employment is a prime driver for improvements in urban regions. Modest or even substantial capacity-oriented corridor or network improvements, often at great cost, may not be sufficient as growth continues and capacity or efficiency gains are soon overtaken. Two example regions that have now turned to applying advanced operational strategies to address continued congestion growth illustrate this observation:

- I-25 underwent significant widening under the $1.67 billion "T-REX" project between 2001 and 2006. However, a 40 percent increase in traffic volumes between 2006 and 2015 eroded the project benefits. Colorado DOT has turned to a managed motorways demonstration to recapture those benefits, and seeks to gain the equivalent of a new lane through this advanced operational strategy at a fraction of the cost.
- US 75 north of Dallas was fully reconstructed between 1992 and 1999, in one section as a depressed freeway with cantilevered frontage roads due to right-of-way constraints. The $600 million project expanded the freeway from four to six lanes to eight.

TABLE I-4 Redevelopment in an Urban Corridor/Region Case Study

Selected Urban Corridor/Region Case Studies	Improvement Approaches
Iway I-195 Relocation	Preservation: Pavement/bridge reconstruction—I-195 alignment shifted 2,000 feet to the south opening over 35 acres of prime waterfront property to redevelopment in Downtown Providence (5 miles of new city streets, 4,100 feet of new pedestrian river walks, and the restoration and improvement of India Point Park) Capacity: Interchange reconstruction—reconfiguration of all highway ramps between I-195 and I-95, eliminating sharp curves and short weaves; reconfiguration of ramps between the two highways and Downtown Providence Some widening from 3–4 lanes plus auxiliary lanes to 4 lanes plus auxiliary lanes

Light rail transit also opened along the corridor in 1998 and a concurrent flow HOV lane in 2007. Continued population and employment growth—the Dallas region has been adding roughly 1 million people every 7 to 8 years—has driven a need for further improvement, but without any possibility of further corridor expansion, integrated corridor management incorporating the existing freeway, light rail, and parallel arterials became an operational solution worth investigating.

Evolving Urban Characteristics

Large urban regions also exhibit evolving corridor or network characteristics that have influenced the selection of improvement approaches. Aside from absolute growth in population and travel destinations—most especially employment—mature urban regions' clustering of origins and destinations can change (organically or by design/policy) and its overall geographic extent tends to grow over time. For example:

- I-66 in Northern Virginia stretches across a corridor extending west from the Washington, DC, metro area, with higher growth and more vacant land at the west end, and lower growth and increasing density and land redevelopment at the east end, thereby driving a need for greater capacity along the full corridor as the metropolitan region grows.
- Similarly, employment growth and rising housing costs/cost of living in San Diego County have led to significant population and housing growth in southwestern Riverside County to the north. Commuter traffic along I-15, the principal inland north–south route between northern San Diego and Riverside Counties and downtown San Diego has seen resultant growth in congestion, delay, and reduced travel time reliability.
- The I-405 corridor east of Seattle was originally constructed in the mid-1960s as a bypass, but it now serves as an intra-suburban and suburban-urban commuting corridor connecting several suburban cities with significant employment destinations, as well as providing connection to several east–west routes that access downtown Seattle.
- The San Francisco Bay Area today is characterized by polycentric employment destinations (and living origins) with major tech companies from downtown San Francisco to the South Bay/Silicon Valley, manufacturing sites for various industries in the East Bay (e.g., Hayward and Oakland), and the state's largest cluster of life science and biotech companies, as well as educational institutions and national labs throughout the region—all driving a need for regional mobility solutions.

Network Planning and Regional Collaboration

Urban improvement approaches at the regional scale suggest several observations about network planning and regional collaboration. Here it is often difficult or impractical to isolate deficiencies and improvements at the Interstate corridor level. It is necessary to evaluate them across non-Interstate elements as well, including arterials, and to consider the impacts and effects of parallel or complementary transit service. For example, the San Francisco Bay Area Express Lane Network include Interstate, state route, and U.S. route segments. Parallel arterial capacity and transit service were weighed in the evaluation of scenarios along the I-15 corridor through the Salt Lake City Metropolitan Region. Multimodal options and the use of parallel routes (often arterials) are essential elements of integrated corridor management, for which a focus on optimizing the throughput of a constrained urban Interstate corridor must broaden out to all corridor options in the face of limited capacity expansion opportunities. Finally, improvement approach feasibility and selection may depend to a greater degree on the number of agencies involved and their institutional context.

- In the Bay Area, the metropolitan planning organization (MTC) has lead planning for express lanes and the development of the long-range plan that programs all projects, but actual implementation responsibility is divided among MTC and two county-level agencies, and furthermore, design and construction is the responsibility of the state DOT, Caltrans.
- Express lane planning in Southeast Florida has been led by Florida DOT, with collaboration from the state toll agency, metropolitan planning organizations, and regional toll authorities.
- The Wasatch Front Central Corridor Study examining a host of improvement approaches was co-led by two metropolitan planning organizations, with collaboration from the state DOT and the regional transit agency.
- Strong institutional partnerships among regional entities are necessary to enable successful integrated corridor management systems. San Diego's MPO, the San Diego Association of Governments, is the lead agency for the I-15 Integrated Corridor Management (ICM) that also relies on collaboration and coordination among the state DOT, state police, two transit agencies, three cities, local first responders, law enforcement, and county emergency services. All participants have agreed on "posture responsiveness" that characterize the nature of actions plans and operation of subsystems that comprise the ICM system based on corridor demand and impact of the event. A certain level of individual agencies' operational control is forgone while trust is placed in the collective response of

all partners based on the ICM system's decision support system's recommendation.

Incremental Approaches

Generally urban improvements with a capacity element are expensive and technically or politically challenging. An incremental approach may be necessary depending on individual corridor or corridor segment feasibility and financial capacity.

- Along the I-405 corridor near Seattle, dual express toll lanes were necessary from an operational performance perspective, but initially only financially feasible for 10 of the corridor's 17 miles. In the long term, a second ETL will be added, but in the short term other incremental solutions have been applied, including additional GP lane capacity via auxiliary lanes where possible and selected transit use shoulders. Post-project completion, Washington State DOT added a peak-use shoulder lane where most needed, paid for with toll revenues collected on the express toll lanes.
- The San Francisco Bay Area Express Lane Network has been refined over time through several planning cycles and has now moved into full-fledged implementation that balances what is most feasible with what is most needed in the near-term. Evolving corridor demand patterns continue to drive refinements to what segments are included and in what sequence they will be implemented.
- The Southeast Florida Express Lane Network is undergoing aggressive implementation with significant, dedicated state funding. In fact, regional express lane planning is occurring statewide. Corridors in Southeast Florida typically involve reconstruction and widening, as opposed to projects found in other regions that exclusively or partially incorporate simpler lane conversions with comparatively little new capacity. The state made a policy decision in 2013 to toll all new capacity in the state, meaning new Interstate/freeway capacity will necessarily be express toll lanes.
- The Iway project in Providence has extended across many years, with the environmental analysis under way throughout the 1990s and construction from the early 2000s, with the hallmark Iway Bridge opening to service in 2007 and all new roads, bridges, and ramps in use at the end of 2010. Related work restoring local streets and completing new development projects in the 35 acres of land opened by the relocation of the highway is ongoing as of 2017. Work to realize this vision for the redevelopment of downtown Providence has extended over 30 years.

Roadway Reconstruction Costs

The roadway reconstruction costs in small urbanized (population between 50,000 and 200,000) and large urbanized (population greater than 200,000) areas cannot be estimated effectively for two reasons: first, bid tabs were unavailable because the case study projects in urbanized areas were procured using design-build and public–private partnerships, and second, because the case study projects in urbanized areas in other areas included significant work on bridges, ramps, and interchanges, the roadway reconstruction costs could not be effectively segregated from other items.

Interurban/Freight Corridors Traversing Urban Centers

Capacity-focused improvement approaches are predominantly found outside the largest urban regions. Significant Interstate projects in this regard exist along key interurban and freight corridors, often where Interstate through-traffic mixes with local, urban (often commuter) traffic exposing safety deficiencies and creating bottlenecks. As summarized in Table I-5, these deficiencies have been addressed with:

- New capacity either along existing right-of-way (likely incorporated into full corridor reconstruction) or new/re-alignment
  - Widening: express and local lanes on I-80/I-29 (Council Bluffs, Iowa), new lanes along I-35 (Waco, Texas)
  - New connections/linkages: Ohio River Bridges' new I-65 Bridge and East End Crossing
  - Realignment: US 93/US 95 (part of Future I-11)
  - New alignment/bypass: Future I-11 (Boulder City, Nevada)
- Interchange addition, reconstruction, or reconfiguration
- New bridges or bridge widening and/or reconstruction

Rural Corridors

Rural corridors typically do not face the same kinds of constrained right-of-way challenges found in urban regions, except where challenging or sensitive geographical features may be found. Rural corridors tend to require improvement approaches in the form of (see Table I-6):

- Traditional widening projects to accommodate rural mobility and accessibility needs and intrastate/interstate truck freight volume growth.
- Functional upgrades or correction of design deficiencies to accommodate volume growth and/or improve safety through access control and grade separation.

TABLE I-5 Predominant Improvement Strategies in Interurban and Freight Corridor Case Studies

Selected Interurban/Freight Corridor Case Studies	Capacity Improvement Approaches
I-65 Ohio River Bridges	Downtown Crossing: Building a new I-65 bridge with six NB lanes (Segment 2) Reconfiguration of Kennedy Interchange (I-64, I-65 and I-71) (Segment 1) East End Crossing: **New East End Bridge 2,500 feet (Segment 5)** **3.5-mile extension of KY 841 from I-265 to East End Bridge** (Segment 4) Reconfiguration of Partial Interchange at US 42 (Segment 4) 1,700-foot tunnel under US 42 and the historic Drumanard Estate (Segment 4) 4.5-mile new roadway from East End Bridge to Lee Hamilton Highway (Segment 6) New interchange at Old Salem Road (Segment 6) Reconstruction of the SR 265/SR 62 interchange (Segment 6)
I-80/I-29 Dual Divided Freeway	Capacity addition from 6 lanes to 14 lanes Reconstruction of two interchanges Other improvements include (i) new bridge over UPRR, (ii) rebuilding of Nebraska Ave and Madison Ave Interchanges, (iii) new I-29 SB lanes and bridges for US 275/Iowa 92, four Interstate ramps, and (iv) railroad consolidation
Future I-11 Boulder City Bypass	Phase 1: US 93/95 Interchange New diamond interchange with connector ramps and 1.5 mile-frontage road Realignment of US 93/US 95 to develop an access controlled 2.5-mile from Foothill Drive to Silverline Road, with 1,200-foot-long retaining wall and 5 miles of tortoise fencing 360-foot long steel truss bridge under United Pacific Railroad Phase 2: BC Bypass New 12.5-mile, limited access, 4 lane divided highway facility at a design speed of 70 mph as bypass to US 93 (Future I-11) New interchange at US 95 intersection (with 3 bridges) Reconfiguration of existing Nevada interchange at SR-172 8 bridges = 3 over intersecting streets, 3 over deep canyons, 1 over drainage way, and 1 for wildlife crossing Scenic view parking area
I-35A Waco Project 5A	Access upgrade Conversion of frontage roads to one-way operations General-purpose lane additions—widening from 2 to 3 lanes

TABLE I-6 Predominant Improvement Strategies in Rural Corridor Case Studies

Selected Rural Corridor Case Studies	Improvement Approaches
I-69 Upgrade of US 77 to Interstate Standards	Preservation: Highway and interchange reconstruction, pavement reconstruction Operations: Geometric improvements Capacity: Interchange improvements and additions
I-15 Rural Corridor—Utah	Capacity: Lane additions (including bridge widening), interchange upgrades, new interchange
I-75 Reconstruction	Preservation: Road reconstruction of 9.38 miles (no capacity addition but with provisions for future expansion), pavement reconstruction, bridge replacement Operations: Realignment of intersecting roads, flattening of curves, noise walls Capacity: Reconstruction of five interchanges
I-80 Connected Vehicle Pilot	Operations: ITS Technology: Connected vehicle applications to improve situational awareness, communications, and traveler information dissemination • Roadside units, mobile weather sensors I2V • Onboard units (trucks and snowplows) V2V, V2I

Among the case study projects in rural areas (population less than 5,000), the average cost of reconstructing a lane is estimated at $1.3 million per mile, while adding a lane is estimated at $2.8 million per mile. For small urban areas (population between 5,000 and 50,000), the average cost of lane reconstruction or addition is approximately $2.8 million per mile. See Table I-11 for additional detail.

The application of technology to address operational and safety concerns in rural corridors is likely to be a growing improvement approach along rural corridors, especially those critical to interstate and intrastate freight movement. The connected vehicle pilot along I-80 in Wyoming is the best example of this.

Interchanges

Several case studies examine the reconstruction or addition of new interchanges as a capacity improvement to address mobility, safety, and accessibility issues interchange projects of both types—service and system interchanges—form a significant portion of the Interstate construction activities in all geographic areas. These projects involve reconstruction and reconfiguration of existing interchanges as well as new interchanges along the corridor to address capacity, access, and operational needs.

The interchange reconstruction and reconfiguration projects were predominantly driven by capacity, operational and structural needs in response to substandard or outdated design standards, higher V/C, poor level of service, higher crash rates, and structural deficiencies. Depending on the needs, these projects may entail a wide range of activities, such as reconfiguration and localized improvements, widening, structure replacement, realignment or relocation, and major improvements to intersecting roads.

The most common service interchanges (i.e., one or more movements must stop at a stop sign or signal or yield at yield sign to movements on the other intersection roadway) that are in use today are diamond and partial cloverleaf interchanges. Inherent to these interchange types are operational and safety problems associated with left turns and conflict points. In addition, when the need for capacity expansion arises, both these interchange designs require a larger footprint, and thus, causing cost and right-of-way challenges in urban areas. The reconstruction of service interchanges involving structure only replacement or installation range between $2 million and $6 million; if major improvements such as widening are included, the cost range can be between $25 and $50 million. Construction of new service interchanges indicate roughly range from $30 million to $55 million. Table I-11 provides additional cost information.

When these interchanges reach structural and/or operational performance thresholds, many agencies are increasingly exploring alternative designs in urban areas, including diverging diamond interchanges (DDI), single-point urban interchanges, and double roundabouts. These alternative interchanges are reported to provide significant reduction in crash rates. On the I-590 Winton Road Interchange Reconstruction project, the selection of DDI resulted in significant cost savings for the right-of-way purchase and projected to result in shorter traffic times, fewer and less severe crashes due to elimination of many conflict points, and fast construction. To date, more than 25 states have installed DDIs. Similarly, double or triple drop roundabouts are gaining prominence in states, such as Colorado and Pennsylvania. The reconfiguration of existing service interchanges with DDI exhibits a cost range of $3 to $8 million (see Table I-11). The reconfiguration of existing service interchanges with roundabouts or single-point urban interchanges ranges from $11 to $18 million.

The reconfiguration and reconstruction of system interchanges (i.e., freeway to freeway, or all free-flow movements from one roadway to the other, and vice versa) in urban areas, such as the Kennedy Interchange in downtown Louisville where I-65, I-71, and I-64 intersect and the I-80/I-29 East and West System in Council Bluffs, Iowa, are driven by similar set of capacity, operational, and structural needs. However, the system interchanges are more complex in configuration with multiple legs, vertical roadway levels within the interchange, structures and loops, and thus, involve multi-year, multi-phase, expensive projects with costs typically more than $100 million. (Four selected system interchanges from three case study projects ranged between $72 and $600 million.) However, as discussed in following sections, the interchange improvements in urban areas are projected to mitigate performance issues in the near term; however, these benefits may not be sustainable in the longer horizon with increasing future traffic demand.

New system and service interchanges are being built to (i) create new or realigned access, (ii) upgrade grade-separated intersections to interchanges along the corridor to reduce congestion and streamline traffic flow, and (iii) convert at-grade intersections to interchanges when non-Interstate highways are upgraded to Interstate standards.

Roadway Assets

Roadway assets are project elements that can be found in all three case study categories discussed above, aside from interchanges. Major elements addressed in several case studies include pavements and bridges.

Pavements

The improvement approaches associated with pavements are preservation methods and life-cycle design and cost considerations. Technology may also be applied in the form of long-life structural designs.

The case studies focused only on the pavement reconstruction projects of existing roadways: I-8 pavement reconstruction in Imperial County, California, and I-75 roadway reconstruction in Allen County, Ohio. In both case studies, the life-cycle-based end-of-useful life considerations, as influenced by historical pavement condition and remaining service lives, primarily influenced the decision to reconstruct. The engineering decisions for reconstruction were optimized to produce pavement designs with minimum practicable life-cycle costs over a longer horizon by adopting the recent advances in materials, and engineering design methodologies such as the innovative long-life design concepts. While it is a common practice to optimize pavement designs and subsequent rehabilitation cycles for a 30- to 50-year period, the I-8 reconstruction adopted a design that required no major rehabilitation activity for at least 55 years.

Pavement reconstruction also provided opportunities to mitigate or eliminate underlying causes of premature pavement failures. For instance, the existing pavement section within the Ohio I-75 roadway reconstruction project historically exhibited poor performance due to drainage issues in subbase and foundation. The pavement was repaired, rehabilitated, and resurfaced with bituminous overlays five times between 1973 and 2004. Each rehabilitation event produced a service life of 8 years in comparison with the expected life of 12 years for this group of pavements. Total reconstruction was required to address recurring issues deep within the pavement structure.

Among projects in rural and small urban areas that involved widening or reconstruction, the cost of pavement installation was approximately $1.3 million per mile. The case studies did not provide a corresponding estimate for small or large urbanized regions.

Bridges

Preservation and capacity improvement approaches to bridges are incorporating longer service life designs, especially using greater material durability, and optimized life-cycle plans governing future bridge maintenance, rehabilitation, and replacement decisions.

The case studies primarily focused on bridges with complex structures, such as cable-stayed bridges, that involve long spans, high vertical clearances, and typically located over water. Four complex bridge structures analyzed under three case studies ranged in unit cost from $480 to $630 per square foot (see Table I-11). This cost range was also influenced by the application of 100-year service life designs. By comparison, the 2016 National Bridge Inventory estimated the national average bridge cost on the NHS as $213 per square foot, ranging from $62 per square foot in Texas to $674 per square foot in Hawaii.

Most of the bridges on the Interstate System, which were originally built in late 1950s and 1960s, were designed for a design life for 50 to 75 years with HS-20[1] loading assumptions. Recent projects, particularly complex bridges, are adopting 100-year "service life" based designs using newer design standards (e.g., updated seismic design criteria) and heavier loading configurations (e.g., HS-25 and HL-93). The case study bridge projects—I-710 Gerald Desmond Bridge in Port Long Beach, I-65 Abraham Lincoln Bridge in Louisville, and I-265 East End Crossing Bridge, the latter two part of the Ohio River Bridges project, as well as the technical evaluation of the I-535 Blatnik Bridge over Saint Louis River in Duluth, Minnesota—adopted 100-year service life based designs.

Life-cycle engineering considerations are increasingly considered in the selection of the type and timing of bridge rehabilitation and replacement strategies. In response to the structurally deteriorating I-535 Blatnik Bridge, the Minnesota DOT (MnDOT) commissioned a technical study to investigate various bridge rehabilitation and replacement strategies for restoration

[1] The HS-20, which was the design standard in the early 1950s, consists of a hypothetical vehicle, i.e., tractor truck with semi-trailer, with 8,000 lbs. on the front single axle and 32,000 lbs. on each of the two tandem axles. The HS-20 is considered the minimum design load recommended for bridges on Interstates.

of structural and functional adequacy of the bridge. The technical study, which involved detailed structural, life-cycle cost and risk analysis of 12 different scenarios, has provided a template for MnDOT to make optimal life-cycle based decisions.

Looking Beyond the Next 20 to 30 Years

The sections above outlined key observations for three broad case study categories based on projects being implemented in response to the contexts of today—the drivers, deficiencies, applications of technology, and regional geographic, demographic, and regulatory/institutional environments. It may be possible to forecast what types of improvement approaches may be necessary as each of the three case study category regions continue to evolve, in some cases from one to another.

Rural Corridors

Rural corridors may tend to remain rural well into the future, and continue to require incremental capacity upgrades as today. Corridor demand growth and travel patterns also may cause some rural corridors to begin to exhibit the deficiencies of today's interurban/freight corridors, requiring in the future the more complex capacity upgrades applied in those contexts. Connectivity may begin to significantly address certain operational and safety concerns associated with incidents (weather, crashes, work zones, etc.). The affordability of long-term maintenance in low-volume rural regions or rural regions with a high percentage of Interstate volume may be a growing concern.

Interurban/Freight Corridors

Interurban corridors of today may start to exhibit the challenges of constrained urban environments in the future. Even now, the level of service improvements from, for example, capacity improvements of the Ohio River Bridges project are only marginal, and congestion is forecasted to return in the long term. Operational and demand management strategies, especially pricing as applied today in large urban regions, may become required in these contexts.

Urban Corridors/Regions

Large urban regions may continue to deploy priced managed lane facilities and networks, but urban physical constraints will only get more challenging. In some cases, it may become necessary to consider full corridor pricing to physically (trip diversion to alternative routes or modes) or temporally (shift in trip time of day) optimize the usage of all capacity. Other demand management and integrated corridor/multimodal strategies, often incorporating a pricing element, will also be deployed to optimize corridor performance from a person throughput perspective. Two approaches poised to move from demonstration status to the mainstream are integrated corridor management and managed motorways.

A number of urban regions are preparing planning studies and concepts of operation for ICM including Fort Lauderdale, Kansas City, New York City, Philadelphia, Phoenix, and others. Caltrans opened a relatively less complex ICM system than the one in San Diego along the stretch of I-80 between the Carquinez Bridge and the Bay Bridge in Contra Costa and Alameda Counties. It is more likely that future ICM systems will be implemented incrementally rather than as one full, multimodal and multi-strategy system, as with the San Diego and Dallas pilots.

Post-demonstration, SANDAG continues to operate and maintain its ICM system. It has further lowered the threshold to activate the system during an incident, increasing reliance on the decision support system and partners to manage system components. SANDAG is also considering applying segment-based thresholds to account for the variability in traffic and incident impact conditions along the full corridor. Continued growth in traffic along the corridor will only continue to make the system indispensable.

The managed motorways concept has the potential to increase the throughput of congested urban-suburban Interstate corridors without adding new lane capacity by optimizing access and therefore the distribution of vehicles along the Interstate corridor itself. Colorado's experiment with the managed motorway technology will have important repercussions around the United States. State DOTs in Utah, Georgia, and North Carolina are following the pilot with great interest and if the results are positive they are likely to advance managed motorway tests of their own.

The Wasatch Front Central Corridor Study in Utah has addressed some of these future scenarios for I-15, choosing to recommend the improvement approaches summarized in Table I-7 (those listed relate specifically to the Interstate; the study made additional recommendations pertaining to arterials, transit, active transportation, etc.).

In all cases, the effects of rapidly evolving technology, especially connected and automated vehicles must be taken into account. Additionally, several major metropolitan regions have stated that the next iterations of their long-range plans will include greater consideration of technology applications, especially CV/AV, in the evaluation and selection of improvement projects.

TABLE I-7 Improvement Strategies for I-15 Corridor

I-15 Urban Corridor—Utah	Improvement Approaches
Operations	Choice Architecture TDM Strategies (application of behavioral economics to incentivize travel choices that benefit system as a whole) Comprehensive TDM Strategy (TDM elements used by existing Traffic Management Associations in the region) Fully-priced Freeways with Barrier-separated "Reliability" Lanes
Capacity	Expanded Collector-Distributor System (Separate but parallel roadways that connect to freeways reducing congestion from freeway entrances and exits) *[Assumed as baseline by 2050]* Managed Motorways, Express Lane Widenings, all highway/transit expansions in 2015 long-range plan
Technology	Pay-Per-Use Transportation App ("Mobility as a Service") (Subscription-based package of transportation services, e.g., bike share, car share, Uber/Lyft, transit trips)

FORECASTED FUTURE PERFORMANCE

Travel Demand

The case studies gathered information on both travel demand and available metrics related to mobility, travel mode share, and safety. Travel demand, in terms of average daily traffic or VMT, is expected to grow annually by geography (see Table I-8). As observed in the case studies, travel demand in urban corridors/regions is expected to grow by 0.5 percent to 2 percent. Lower growth is generally observed in the denser urban environment, such as the easterly segments of I-66 in Fairfax County and San Francisco Bay Area, where future land use patterns trend toward repurposing for higher land use intensity, whereas, higher growth is observed in suburban segments of the corridor, such as the westerly segments of I-66 in Prince William County, where vacant lands are being developed to cater to more affordable housing needs.

Travel demand along interurban/freight corridors is generally forecast to grow by 2 to 3 percent. These forecasts are apparently based on projected increases in population and employment in mid-size cities as well as increases in freight traffic due to economic growth. Rural regions tend to see forecast growth rates of 1 to 2.5 percent, although the case study sample size is small and varied. Freight traffic is also a significant contributor to this expected growth in rural regions. Many of the case studies categorized as interurban/freight corridors, rural corridors, and roadway assets carry significant proportions of trucks and are identified within transcontinental freight networks.

TABLE I-8 Estimates of Annual Growth in Travel Demand

Case Study	Case Study Category	Travel Demand Growth Estimates
VA I-66	Urban Corridors/Regions	Westerly Segments = 1.0 to 2.5% Easterly Segments = 0.5 to 1.0%
WA I-405	Urban Corridors/Regions	1 to 2%
CA Bay Area	Urban Corridors/Regions	1%
UT I-15	Urban Corridors/Regions	1.2 to 1.7%
RI I-195/I-95 (Iway)	Urban Corridors/Regions	0.7%[a]
KY-IN I-65 ORB	Interurban/Freight Corridors	1.90%
NV Future I-11	Interurban/Freight Corridors	2.70%
IA I-80/I-29	Interurban/Freight Corridors	3.10%
TX I-35A	Interurban/Freight Corridors	1.7 to 2.0%
TX US 77 Upgrade	Rural Corridor	2.61%
OH I-75	Rural Corridor	1.4%[b]
CA I-8	Roadway Assets—Pavement (Rural Region)	1.2 to 2.3%
NY I-590	Interchange (Urban Region)	0.7 to 0.8%[c]

[a]Peak period estimates from 1990 to 2015.
[b]Forecasted growth between 2002 and 2032. Actual growth between 2002 and 2016 was –0.7 percent.
[c]Forecasted growth between 2005 and 2028. Actual growth between 2002 and 2014–2017 was significantly greater than forecast along I-590 but well below forecast for the Winton Road ramps. NYSDOT could not offer an explanation for this disparity.

Mobility

Urban Corridors/Regions

Mobility metrics reported for urban corridors focused predominantly on peak hour throughput and travel time. These metrics were generally derived using microsimulation models such as CORSIM and VISSIM. In comparison with the no-build option, the introduction of managed lanes has an apparent positive effect on the mobility performance of GP lanes. For example, as observed in I-66 and I-15 corridor studies, the travel times on GP lanes are expected to decrease by 45 percent and 4 to 30 percent, respectively, in the future (i.e., 2030–2040), while the I-405 and Bay Area express lanes show about 40 percent and 15 percent improvement in travel speeds, respectively.

The managed lanes are expected to carry a significant share of the vehicle throughput, particularly during the peak hour periods. The peak hour vehicle throughput indicate a share of 70:30 on general purpose and express lanes on the South East Florida Express Lane Network, 67:33 on I-66 and 45:40 on the I-15 corridor. Among the case studies presented, only actual operating data for the I-405 Express Lanes is available (see Table I-9). The forecasted mobility metrics (volumes and speeds) of I-405 Express Lanes compare well to actual usage during the first 15 months of operation. However, note that the forecast and actual peak periods are not identical; the actual peak periods are longer than originally forecasted.

The combination of managed and GP lanes collectively results in improvements to vehicle and person throughput as well. When compared with the GP lane only option, both managed and GP lanes are projected to increase vehicle throughput by 33 percent on the I-66 corridor and 73 percent on the I-405 corridor. Person throughput is estimated to improve by 43 percent on the I-66 corridor. The managed lanes are expected to shift away a portion of GP lane person throughput, for example about 8 percent on the I-66 corridor, apparently through toll-free incentives for high occupancy vehicles and bus transit options.

Emerging advanced operational strategies applied to urban corridors—integrated corridor management and managed motorways—are also intended to improve mobility focusing on delay reduction/travel time savings and travel time reliability. The three demonstration projects illustrating these techniques are new enough not to have robust performance results reported, but nonetheless analysis, modeling, and simulation techniques have produced performance estimates for the two ICM pilots, and the managed motorways demonstration is aiming to achieve mobility improvements in line with what has been observed in Melbourne Australia's M1 Motorway on which the demonstration is based. These three pilots' mobility metrics are summarized in Table I-10.

TABLE I-9 Comparison of Forecasted and Actual Mobility Metrics of I-405 Express Lanes

I-405 Express Lanes Dual ETL Section	GP	ETL	Total	% ETL
Forecast (6–9 AM)	15,700 (43 mph)	8,000 (60 mph)	23,700	34%
Actual (5–9 AM)	17,200 (44 mph)	8,600 (59 mph)	25,800	33%
Forecast (3:30–6:30 PM)	13,700 (32 mph)	8,090 (60 mph)	21,790	37%
Actual (3–7 PM)	19,300 (30 mph)	9,900 (56 mph)	29,200	34%

TABLE I-10 Mobility Improvement Metrics—ICM and Managed Motorways Demonstrations

	Mobility: Person-Hours Traveled/Year	Improved Versus Worsened Travel Times (Differential)	Reliability: Buffer Time(s)	Variability: Avg. Travel Time(s)
I-15 ICM San Diego				
SB AM—without ICM	14,302,100	—	142.5	636.7
SB AM—with ICM	14,192,500	—	138.8	632.2
Improvement	0.8%	+4.0%	2.6%	0.7%
NB PM—without ICM	19,248,800	—	132.5	635.0
NB PM—with ICM	19,090,200	—	126.6	629.0
Improvement	0.8%	+2.7%	4.5%	0.9%
Annual Delay Reduction	268,200			
Improvement	3.3%[a]			
US 75 ICM Dallas				
SB AM—without ICM	19,782,900	—		
SB AM—with ICM	19,775,600	—		
Improvement	0.04%	+1.0%		
NB PM—without ICM	15,503,000	—		
NB PM—with ICM	15,492,800	—		
Improvement	0.07%	+1.4%		
Annual Delay Reduction	17,500			
Improvement	0.14%[b]			
	Average Traffic Flow (vphpl)	**Average Travel Speeds**	**Travel Time Reliability**	
SMART 25 Managed Motorways Denver—Benchmark Performance from Melbourne Australia M1 Motorway, VicRoads				
AM Peak	4.7%	34.9%	148.7%	
PM Peak	8.4%	58.7%	516.4%	

[a]Based on 35 hours of annual freeway delay per person and AADT of 230,000.
[b]Based on 49 hours of annual freeway delay per person and AADT of 250,000.

Interurban/Freight Corridors

Mobility metrics reported for interurban/freight corridors included volume/capacity ratio, travel time and speed, and intersection level of service. For these case studies, the proposed capacity expansion strategies are expected to bring immediate improvements in freeway and interchange LOS. Although the magnitude of performance improvements vary from project to project, the model forecasts generally indicate a terminal design year LOS of C, D, or E for all case study projects.

For instance, the Ohio River Bridges project increased the number of lanes from 3 to 8 to facilitate the mobility of north–south I-65 traffic across the Ohio River. The congestion LOS estimates for the I-65 bridges show marginal improvement from F for no-build to C or D for the as-built alternative. Similarly, on the Future I-11 project, the construction of the Boulder City Bypass, a tolled facility, would divert about 20 percent of traffic on US 93; yet, the LOS of interchanges along US 93 is expected to show marginal improvement from E to D in the future.

Terminal LOS estimates of C, D, or E lend themselves to questions about the performance expectations of the facility beyond the future design year, which is only about 15 to 25 years into the future. In other words, future LOS expectations raise questions about the sustainability of capacity expansion strategies to alleviate congestion in mid-sized cities and whether the highway agencies should look beyond to incorporate new operational and technical driven strategies in the future.

Safety

The existing conditions of most facilities, particularly those with interchanges, exhibited safety deficiencies with crash rates higher than region-wide or state-wide crash rates. Poor safety performance of these facilities was primarily attributed to inadequacy of auxiliary lanes for weaving, merging, and diverging movements. This trend was observed on I-66, I-65 (Kennedy Interchange), and I-80/I-29 (East System Interchange). However, with the exception of the I-66, as well as the I-15 case studies, safety was not a primary deficiency driving the project, data were unavailable, or available safety data were questionable or did not capture a full 3-year post-construction period. Two examples that capture this last point are the I-590 Winton Interchange for which lack of intersection capacity contributed to accidents and the I-75 Reconstruction for which outdated design standards contributed to crash rates higher than the statewide average.

For the I-590 Winton Interchange, accidents at the intersection between Winton Road and the I-590 northbound and southbound ramps increased by 8 percent in the 3-year period between 2014 and 2016 compared with

2006 to 2008 (construction took place in 2012). It seems unlikely that driver acclimation to the novel configuration of a diverging diamond interchange would have contributed to the increase, since available post-construction safety data begins more than 1 year after construction completion. It is possible data accuracy or analysis consistency affected the comparison. Before-and-after traffic volumes are not available to qualify the accident data in terms of intersection usage.

I-75 Reconstruction crash rates immediately post-construction (less than 1 year) are higher than the 6 years prior to construction (1.55 versus 1.13 for PDO and 0.37 versus 0.24 for injuries), although they were lower than measured during the 3-year construction period. This sample is insufficient to comment on the project's safety impact conclusively. A full 3 years of post-construction data would be needed to draw firmer conclusions on the project's effect on safety.

Most projects involving technology or demand management are designed to be safety neutral. This was explicitly concluded for the I-15 and US 75 ICM demonstration projects and generally understood to be true for express lane projects. Further research on the safety impacts of express lanes is an identified need, however.

While the SMART 25 demonstration of the managed motorways operations is slated to begin in 2018, the project relies on the same technology and operational strategies as the M1 Motorway in Melbourne, Australia. The managed motorway system regulates the flow of vehicles entering congested highway corridors, limiting stop-and-go conditions and traffic instability. During the first 2.5 years of manage motorways operations on the M1, there has been a 12 percent reduction in crashes. This includes a 19 percent decrease in fatal crashes and a 10 percent reduction in serious and other crashes. Since the inception of managed motorway operations, casualty crash rates (per 100 million vehicle-kilometers traveled) on the M1 are lower than on other freeways in metropolitan Melbourne.

Analysis Models

Two major categories of analytical models were reported in project-level and planning-level documentation of case studies:

- Travel Demand Model—Almost all studies utilized a regionally calibrated model developed by their regional or metropolitan planning organization for travel demand forecasting. For instance, the Bay Area study utilized the Metropolitan Transportation Commission's Travel Model One model, while the Future I-11 project utilized the travel demand model developed and maintained by the Regional Transportation Commission of Southern Nevada.

- Traffic Simulation Models—Microsimulation models, including VISSIM and CORSIM, were used to simulate traffic flow and develop mobility metrics for I-66, I-405, I-65 (Kennedy Interchange), and I-80 connected vehicle projects. Other projects, including Future I-11 and I-8/I-29, utilized models in the Highway Capacity Manual software.

The I-15 and US 75 ICM demonstration combined use of both regional travel demand models and microsimulation software for analysis, modeling, and simulation exercises applied to refine application of ICM features and forecast performance. In the I-15 ICM case, the microsimulation software was also integrated into the decision support system to forecast traffic conditions up to 60 minutes in the future and provide real-time simulation and predictive analysis of incident response or congestion management strategies.

Other models were also used for specific purposes, and these include Enhanced Interchange Safety Analysis Tool and Extended HSM Spreadsheets for safety analysis, toll revenue estimation model, DRAM/EMPAL—PSRC land use forecasting model and UrbanSim land use models, and EPA's Motor Vehicle Emissions Simulator (MOVES) for emissions forecasts.

PROJECT COSTS

The case studies captured cost per mile or per asset estimates for each category, which are summarized in Table I-11. The costs in urban areas often depend significantly on the number and complexity of interchanges and bridges. Available cost data often do not disaggregate design components or structures. Cost per mile data may include interchanges, ramps, bridges, and other features, and therefore, the figures should only be used for planning purposes on regional or representative corridor basis.

Operational costs for two express toll lane facilities are also provided, however these costs are being investigated further in a separate exercise under this study.

TABLE I-11 Summary of Project Costs

Case Study	Cost Estimates
Urban Corridors/Regions	
Express Toll Lanes	
I-405 Express Toll Lanes	$15.1 million/lane-mile (new ETL, ROW not included, includes ramps/interchanges) $3.1 million/lane-mile (HOV-to-ETL conversion)
San Francisco Bay Area Express Lanes	$3.0 million/lane-mile (HOV-to-ETL conversion) $7.5–$43.3 million/lane-mile (new ETL; lower end—construction in mostly undeveloped region, upper end—includes 2 reconstructed bridges)
Utah I-15 Urban Corridor	$9 million/lane-mile (new ETL, including some ramps) $2.9–$9 million/lane-mile (new GP capacity)
Demand Management Demonstrations	
I-15 ICM Pilot	$11.6 million (pilot project including planning, deployment, demonstration, and analysis)
US 75 ICM Pilot	$8.4 million (pilot project including planning, deployment, demonstration, and analysis)
SMART 25 Managed Motorways Demonstration	$10.61 million (demonstration total) $6.58 million (construction) $1.60 million (construction contingency and indirect costs) $1.77 million (integration and operations) $632,000/mile (construction)
Interchange/Bridge	
Iway I-195 Relocation	$610 million (pavement, interchange, realignment, widening, auxiliary lanes, bridge replacement)
I-590 Winton Interchange	$8.1 million (DDI including design, ROW, utilities, construction, inspection)
I-710 Gerald Desmond Bridge	$240 million (for cable stayed bridge)
I-535 Blatnik Bridge	$256 million (average), $188–$345 million (range)
Interurban/Freight Corridors	
Pavement/Interchanges	
I-35A Waco Project 5A	$182.9 million $13.65 million/mile (includes 10 interchanges)
I-8 Imperial County Pavement Reconstruction	$1.28 million/mile
Interchanges	
I-80/I-29 Dual Divided Freeway	$37.9 million (Nebraska Ave. interchange) $283 million (East System interchange)
Future I-11 Boulder City Bypass	$109 million (US 93/US 95 diamond interchange)

TABLE I-11 Continued

Case Study	Cost Estimates
I-65 Ohio River Bridges	$600.3 million (I-65/I-64 Kennedy system interchange)
I-85 Kia Blvd. Interchange	$4.38 million (bridge structure only, including design and inspection; does not include ramps and connecting roadways)
I-70 New Stanton Interchange	$53.7 million (includes two roundabouts, auxiliary lanes, park-and-ride lot, bridge deck replacement, improvements to connecting roadways, and reconstruction of 1.7-mile roadway)
Bridges	
I-80/I-29 Dual Divided Freeway	$12.7 million (24th Street Bridge replacement)
I-65 Ohio River Bridges	$242.4 million (I-265 Ohio River Bridge) $339.3 million (I-65 Downtown Bridge)
Rural Corridors	
Utah I-15 Rural Corridor	$2.8 million/lane-mile (lane-additions)
I-69 Upgrade of US 77	$2.25 million/lane-mile $1.3 million/lane-mile (pavement only)
I-75 Reconstruction	$136 million (multiple contracts)
I-80 Connected Vehicle Pilot	$5.76 million (total budget for design and deployment and 18-month demonstration) $1,260/mile (hardware cost per mile)
Operational Costs	
I-405 Express Toll Lanes	$6.7 million (2016 toll collection costs against $20.2 million in revenue; costs do not include O&M of traffic management systems)
595 Express	$503,000 (2016 "toll operating expenses")

Appendix J

Additional Detail on Funding and Financing Options

This appendix provides additional detail on options for funding the needed investments in the Interstate Highway System to supplement the discussion of funding options in Chapter 6. The appendix first elaborates in turn on mileage-based user fees and the use of revenues from carbon pricing and cap-and-trade programs, including pilot programs testing these approaches. The second section examines the possibility of financing improvement projects where traffic is of sufficient volume to allow for borrowing the necessary funds and paying them back with revenues from fees charged to users. The third section details the National Surface Transportation Infrastructure Financing Commission's evaluation of potential taxes and fees associated with highway transportation. The fourth section provides context for the options reviewed in Chapter 6 and this appendix by presenting a high-level review of funding and finance options in other industrialized democracies.[1] The final section provides a rough estimate of federal motor fuel taxes or per-mile fees necessary to raise the additional revenue of the magnitude described in Chapter 6.

[1] The committee appreciates the assistance of Thomas Boast, THB, New York; Remy Cohen, Cohen & Co., Milan; and Jose Manuel Vassallo, Universidad Politécnica de Madrid, for the review of the international perspective in this appendix and provision of helpful references and information about recent developments as of May 2018.

ADDITIONAL FUNDING OPTIONS

Mileage-Based User Fee (MBUF) for All Roads[2]

Both of the national commissions the Congress established in SAFETEA-LU recommend evaluating and moving toward vehicle-miles traveled (VMT) fees[3] to ultimately replace motor fuels taxes.[4] Since those reports were published in 2007 and 2009, the term "VMT fee" has been replaced by "mileage-based user fees" (MBUFs). In the Fixing America's Surface Transportation (FAST) Act of 2015, Congress approved a $92 million pilot program in which many states are participating. As described below, preliminary results are being reported even as several pilots are continuing to collect and analyze data.

At the time of this writing, MBUF pilot projects are under way in California, Colorado, Delaware, Hawaii, Oregon, Washington, and other states, including a 14-state coalition of Western states and the Eastern states participating in the I-95 Corridor Coalition (both coalitions are participating as part of state-funded pilots). Prior research and state pilot projects have explored several important interrelated issues about MBUFs, among them are:

- Public understanding and acceptance, particularly regarding privacy issues;
- Charging criteria (i.e., whether to charge by functional class of highway and jurisdiction, which would allow multiple fees to be collected at the same time, and how to assess the charge, for example, odometer readings, location-based devices, or "pay-at-the-pump" technology that does not include use of particular roads);
- Revenue redistribution (i.e., how to credit mileage accrued outside of states' or localities' jurisdictions or how to distribute it back to other appropriate jurisdictions); and
- Equity.

Understanding and Acceptance

Public awareness and acceptance of the concept of charging a MBUF appear to be quite low (Agrawal et al. 2016), which is not surprising given the novel nature of the concept to most of the public. Opinion polls conducted

[2] This appendix also draws on Kirk and Levinson (2016).

[3] VMT fee is a road charge based on the miles driven by a specific vehicle.

[4] The committee appreciates the assistance of Adrian Moore, Ph.D., Vice President for Education, Mileage-Based User Fee Alliance, for his review and comments on an earlier draft of this section.

for the Washington State and Oregon MBUF pilot projects support this finding (Oregon: Oregon DOT 2017; Washington State Transportation Commission and Washington State DOT 2017). States have used their pilot projects, in part, to test how the public's response changes as experience and familiarity with the concept grows.[5] Support by users has been mixed in early trials. A survey of the participants in California's trial found that "78% were satisfied with the security of their data, 73% agree that road charge is more fair than a gas tax, and 61% were very satisfied with the concept of road charging" (California State Transportation Agency 2017). However, because the participants in this trial were volunteers, there is some question of whether these results are representative of the general, motoring public in California or elsewhere (California State Transportation Agency 2017). In contrast, for example, a majority of the 500 Minnesota volunteers in a pre-FAST Act pilot MBUF program continued to prefer fuel taxes over a MBUF that tracked mileage using a GPS-based system.[6]

Considered to be key aspects of public acceptance, both privacy and the security of data are being explored in most of the pilot projects under way. Among the state pilots, Hawaii is only testing initially for how to charge for mileage based on odometer readings; most other state pilots are testing a variety of mechanisms that would allow for charging by type of road used, jurisdiction, and congestion levels. Minnesota found in its earlier pilot program that participants in its GPS-based program were not particularly concerned about the system's vendor having records of their trips, but were very concerned about hackers gaining access to their data.

Political acceptance is also an issue. For instance, political leaders in Massachusetts and Connecticut resisted plans for pilot projects out of concern that the MBUF would be viewed by the public as laying the groundwork for a new tax (Connecticut: Lee 2017; Massachusetts: Buell 2016). Additional states to those already participating in pilot tests, however, are either moving forward with, or seriously considering, their own evaluations (Missouri: Schmitt 2018; Utah: UDOT 2018). This experience raises an important issue about the viability of MBUFs as a replacement for, or supplement to, fuel taxes—if political leaders are unwilling to raise fuel taxes, would they be any more willing to institute an MBUF and keep its level current with demands for highway investment?

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[5] Public sentiment in Stockholm ran against congestion pricing when a large-scale pilot project began, but this shifted to favorable as residents became familiar with the approach (Eliasson 2014).

[6] This $5 million study was funded by the state and completed before the FAST Act pilot program was established. The complexity of the Minnesota trial, which included safety and trip time estimation in addition to assessing a fee and relied on early generation smart phone technologies, may have affected respondent opinions (Rephlo 2013).

What to Charge for and How

Oregon's evaluation of the initial phase of its pilot program pointed to limitations in all the technology options explored, reporting that imbedded devices did not work in all vehicles, fuel consumption could not be accurately estimated in all vehicles, and devices could be removed from vehicles for periods of time and thereby avoid paying the MBUF (Oregon DOT 2017). Oregon recommended designing systems that are "technology agnostic" as MBUF technology evolves and suggests that MBUFs may have to start at a simple level and mature with technology and public acceptance. Final results from California's pilot, however, suggest that the simple systems that might be rolled out initially are the most expensive to operate and enforce (California State Transportation Agency 2017, 7), whereas the most technologically sophisticated systems (with and without location information) show promise but require refinement. At the time of this writing, California has embarked on an evaluation of the "pay at the pump" MBUF option, developed earlier by Oregon (Whitty and Svadlenak 2009), because of the public's acceptance and familiarity with paying gas taxes. A subsequent phase of Oregon's pilot will evaluate other technologies, which combined with evaluations under way in other states and consortia of states, may find more promising options that reduce overall costs and allow for sophisticated pricing.

Crediting Mileage to Jurisdiction

Aside from Hawaii's pilot (where out-of-state mileage concerns are irrelevant), most pilots are evaluating whether and how to credit mileage accrued in other states. This interest appears to be driven by concerns about fairness and public acceptance. If it proves feasible to document such multi-jurisdictional mileage efficiently, it raises the question of how to transfer funds among states. The complexity of this problem grows with the variety of different charges that states may choose to impose and the number of other jurisdictions with which they exchange funds; this complexity contributes to the relatively high cost of administering MBUF programs (described below). At the time of this writing, the Western state coalition is studying this issue (through the grants to Oregon and California), as is the I-95 Corridor Coalition effort (which is based on Delaware's pilot) and will also test interoperability with toll roads.

Cost of Collection

Initial estimates of the cost of collecting MBUFs are in the range of 5 to 13 percent compared with about 1 percent for the fuel tax (Kirk and Levinson

2016, 4). The federal fuel tax is collected on fewer than 1,000 transactions to fuel wholesalers. A nation-wide MBUF would have to collect information on and bill more than 250 million vehicle owners, so it would, of necessity, be a more complex and expensive proposition. The Western states coalition is exploring the concept of a single multi-state system for collecting data across states, billing users, and handling cross-state transfers in order to achieve needed economies of scale. Clearly, a new approach with a much higher administrative cost than the existing one has an additional hurdle to gaining public acceptance.

Equity

Available summaries from interim results of state pilot projects address some of the equity implications of MBUFs, that Congress asked that pilot projects address. The equity of road pricing strategies are more complex than it might seem on the surface, since equity has so many dimensions (such as income, geography, and user responsibility, among others), and because the equity consequences depend not just on who pays but on how the revenues are used, including cross-subsidies to rural roads and offering alternatives or rebates to those least able to pay (TRB 2011). Some state pilot projects consider the concern that rural residents would pay more than urban residents, but Oregon's study finds the opposite. Urban drivers tend to drive smaller, more fuel-efficient vehicles than rural drivers, so switching to a per-mile traveled fee would cause them to pay more under the MBUF program (Oregon DOT 2017, 6). In general, higher income vehicle owners would pay more than lower income vehicle owners because they drive more. Revenue raising mechanisms that rely on payment from a bank account or by credit card, however, raise an immediate threshold issue for the 7 percent of the population that is "unbanked" (FDIC 2017) and would therefore have difficulty paying unless some subsidy or cash alternative were provided. In terms of equity among tax payers, MBUFs should be a fairer charge to road users than fuel taxes (since electric vehicles do not pay and hybrids pay less that gasoline/diesel-fueled vehicles) and should also be fairer than using general revenues to pay for roads since payment of income and sales taxes does not reflect road use.

Pro—MBUFs are potentially an efficiently targeted user fee because they could be adjusted by weight (to account for road wear), congestion, environmental impact (using vehicle fuel economy as a proxy), and for other purposes. Several ongoing pilot projects have demonstrated technical feasibility, albeit all variations have some important shortcomings. MBUF variations are in use in Europe and New Zealand. European models are restricted to trucks and are applied to assess environmental and road damage. New Zealand does not collect fuel taxes on diesel-fueled vehicles to avoid taxing diesel fuel for farm vehicles. A mileage-based fee has been assessed to New Zealand diesel-powered personal vehicles (based on odometer readings) since 1977 (Kirk and Levinson 2016).

Con—It would be legally questionable for the federal government to require states to impose a MBUF for Interstate use since the Constitution does not give the federal government the ability to compel states to raise fees, but the mandate could probably be conditioned on receipt of federal aid (Kirk and Levinson 2016). An MBUF for the purpose of collecting fees may require location-based devices that generate privacy concerns in order to estimate use of roads within specific jurisdictions or on various road systems. Public awareness and acceptance of the concept of charging a MBUF appear to be low in baseline opinion polls, but experience and familiarity may turn this around. The concept of using pilot studies to explore replacing the fuel tax with a MBUF became politicized in at least two states, indicating political challenges that would have to be overcome. In both cases opponents alleged that the pilot was a stepping stone to a new tax. (Regarding concerns about systems that track drivers' trips, a "pay at the pump" system tested in the earliest Oregon trials demonstrated that such a system could work without tracking drivers, but it would not be able to estimate usage on specific segments of the highway system and, of course, it would not be feasible for alternative fuel vehicles [Whitty and Svadlenak 2009].) As with toll roads, a MBUF would have a higher collection cost—estimated to be in the range of 5 to 13 percent. The cost could be driven down by relying exclusively on electronic transactions, but would have equity concerns because of the individuals not having bank accounts or credit cards. The technology that would be used invokes other complications. An after-market device that would be added to existing vehicles could be easily disconnected. Reliance on devices built into new vehicles could avoid this problem, but given that it takes about 20 years or more for the light-duty fleet to turn over, it would take decades before all vehicles were paying in the same way. California's final report recommends evaluating a pricing system based on mileage measurements gathered from in-vehicle telematics systems, which all new vehicles are expected to have by model year 2020 (California State Transportation Agency 2017, 8). Other possible disadvantages of an electronic MBUF are the cybersecurity vulnerabilities of both the device in vehicles and billing records. One often unconsidered issue is that establishing a rate for per-mile charging may be no less politically fraught than raising the fuel tax (TRB 2006). Also lacking consideration is what level of government would establish the rates. Given that local conditions (such as traffic, construction costs, and feasible alternatives) will be highly influential in determining an appropriate rate, fairness may imply that states and local governments should set rates within their jurisdictions.

As concluded by the Policy Commission, given the growing limitations of the fuel tax, the need to find a replacement or supplement to it, and widespread experimentation with MBUFs, it appears that workable solutions for at least a simple MBUF could be found. It may, however, take considerable time for the public to understand and accept this approach (and it may not) and for implementation to proceed in an incremental fashion. For a general MBUF for all roads to work as a funding source for the Interstate Highway System, some sort of location-based approach may be needed to record trips on the Interstates, and the technology required for this raises the most concerns about privacy invasion (see, however, the MBUF for the Interstates section of Chapter 6 for a possible approach to this problem). Some variations on an MBUF are feasible in the foreseeable future, but a decade or more may pass before they achieve widespread public acceptance and resolve concerns about technology and cost.

Carbon Pricing and Cap-and-Trade Revenues for Transportation

If the nation and individual states were to follow most economists' recommendation to tax carbon as the most efficient way to reduce fossil fuel emissions, it would generate a substantial revenue stream that could be invested in transportation among other options. The Finance Commission viewed these options as potentially strong revenue sources for highway funding and recommended that, if imposed, some share of the funding should be dedicated to the Highway Trust Fund. Lacking specificity about such strategies in the United States, however, the Commission declined to recommend a specific amount or share of the resources.

Carbon cap-and-trade programs are seen as a more politically viable approach to regulating carbon emissions than pure carbon taxes. Carbon cap-and-trade programs are in place in some nations and in California. In 2017, California's legislature revised and extended its program to 2030. Under the previous program, 60 percent of funding generated through auctions has been dedicated to transportation, including high-speed rail, transit, affordable housing (linked to transit), and rebates for purchase of electric vehicles among others (California Air Resources Board 2017). Political debates about the California cap-and-trade program has created uncertainty about the program and the revenues it generates. Although transportation has been a major beneficiary, funds have not been dedicated to highway construction, maintenance, or repair because the purpose of the funding is to reduce carbon emissions. Funds have been invested in transit and other transportation projects and programs believed to reduce carbon emissions. As described in Chapter 6, there are carbon emission reduction strategies that could be employed on Interstate highways to facilitate the adoption of long-distance zero- or low-carbon emission vehicles.

FINANCE OPTIONS

Financing those projects that have sufficient traffic to pay for themselves could serve as a useful supplement to funding. Financing implies that projects that have sufficient demand could be funded by borrowing with the repayment based on revenues charged to users. Many network links, particularly in rural areas, however, may be unable to pay for themselves in this way. Thus, financing should be viewed as a supplemental option to funding. This section reviews public–private partnerships (instruments that can design, finance, implement, maintain, and operate projects); bond finance (a mechanism to attract capital); public sector loans, and loan guarantees (means of extending the creditworthiness of projects).

Public–Private Partnerships

In recent years, the private role in designing, building, operating, maintaining, and financing highways has grown through public–private partnerships (P3s). P3s offer the potential to harness the private sector's ability to design and construct projects faster than the public sector while also bringing in additional funds through equity contributions.[7] P3s can take myriad forms, ranging from relatively simple projects, where the partnership designs and builds a project to be owned and operated by the public sector, to arrangements where a P3 designs, builds, finances, operates, and maintains a highway, bridge, or tunnel, sometimes for decades. P3s depend on either a revenue stream derived from tolls or future public payments, often referred to as "availability payments" to the private partners to reimburse their up-front capital investment and provide a profit. These future payments are typically derived from expected federal or state funding and are similar in some regard to revenue bonds (described separately below).

U.S. experience with P3s in the highway industry has been slowly expanding since the 1980s. Following 1987 authorizing legislation that permitted pilot projects, subsequent federal authorizing legislation up until the present has tended to expand the opportunities for public agencies to partner with the private sector, particularly by allowing wider use of tolls on federal-aid highways (with the exceptions of existing Interstate lane-miles). Investors in P3s are attracted to larger, more expensive projects because they represent a better opportunity to recoup the large up-front costs associated with negotiating with the public sector and funding the costs of moving projects through the lengthy environmental review process. Partly for this reason, P3s, despite their growth, represent a fairly small share of total highway investment. From the quarter of a century from the

[7] This section draws considerably from Mallett (2014).

late 1980s through mid-2015, a total of 21 P3 projects worth $24.6 billion were under way compared to nearly $250 billion in total highway spending by all levels of government in 2014 alone (FHWA 2016, 4, Appendix C).[8] Furthermore, some would argue that such projects merely represent a form of federal borrowing and doing so at a higher effective rate than that at which the government can itself borrow.

Pro—P3s could be attractive for future investments in the Interstate Highway System by accelerating construction or reconstruction and by providing up-front capital to help make these projects possible. Projects that proceed with limited up-front public investment also allow existing annual authorized funding to be spread over more projects. To the extent that P3s can design, build, and complete projects faster than the public sector, they can also reduce total construction costs.

Con—P3s that include private financing that depend on tolls are greatly limited by federal restrictions on tolling existing Interstate roadways. For P3s that depend on "availability payments," it is not obvious what the advantage to the states would be in the long term beyond the fact that a P3 might be able complete some projects faster than a state could with "pay-as-you-go" funding. As with toll roads in general, some P3s have defaulted and required additional state and or federal funding (see Mallett 2014, 5–9). Moreover, not all projects have been deemed to be good deals for the public. Finally, the growth of P3s would not necessarily represent net new funding for transportation if policy makers choose to authorize or appropriate less funding with the expectation that privately financed projects will fill the gap.

P3s do provide opportunities to expand the resource base for future Interstate Highway System funding and could play an important role in maintaining and expanding segments of the Interstate System, particularly if Congress lifts the limits on tolls for existing Interstates. The growth in experience with P3s and availability of technical assistance from the Federal Highway Administration (FHWA) and private-sector advisors may help weed out projects that do not have the potential to succeed. Net benefits depend on whether Congress would view private financing as a supplement to public funding rather than a substitute.

Tax Exempt, Tax Credit, and Revenue Bonds

Financing of public infrastructure improvement projects typically relies on the bond market to raise the up-front capital required. In 2014, the most recent year for which complete data are available, bond proceeds of all types represented 18.8 percent of spending on highways and roads by

[8] For total spending on highways, see Mallett and Driessen (2016, Table 2).

states and 9.5 percent of such spending by local governments (Mallett and Driessen 2016, Table 2). Most state and local government borrowing for roads relies on tax-exempt bonds, referred to as municipal bonds (munis). Munis typically have a lower risk than other bonds because they are backed by the taxing power of the government issuing the debt, which lowers the cost of the project to the issuer of the bonds. Munis also exempt interest payments from federal taxes (and state taxes in many states), which makes the investment attractive, particularly to high-income investors. It should be noted, however, that most pension funds and certain kinds of international investors, both of which are important potential investors in long-term infrastructure projects, are exempt from federal income taxes, so these tax advantages would not necessarily drive investor behavior.

Revenue bonds are a form of muni in which the revenues from a particular source are used to repay bond holders rather than relying on the general taxing authority of the issuing government. They have the same exemption from taxation on interest earned as other munis. However, they pay a slightly higher interest rate due to the lack of backing by the issuing entity's general tax authority. Revenue bonds are typically used to fund capital improvements in municipal water and sewer authorities with repayment based on the revenues earned from ratepayers. In principal, a revenue bond could be repaid from expected future federal or state aid, similar to "availability payments" in P3s, but would likely pay a risk premium due to the uncertainty about future reauthorization of federal and state transportation programs.

Debt issued by private entities of P3s for infrastructure projects can also use qualified private activity bonds, which provide tax exemptions like municipal bonds but are issued by private entities. There is currently a federal ceiling on total issuance of such bonds for transportation infrastructure of $15 billion, of which $6.6 billion had been allocated as of the beginning of 2017 (Build America Bureau n.d.). Private issues of bond debt have also relied on various forms of tax-credit bonds, which provide a tax credit or direct payment to either the issuer of the bond or the investors in the bonds. Congress has authorized tax-credit bonds for limited periods for specific purposes. Recent examples used in transportation infrastructure projects have been Build America Bonds (BABs), for which authority expired in 2011 (Driessen and Stupak 2016, 4). A previous Transportation Research Board study that examined public financial assistance to private financers of transportation infrastructure recommended that Congress treat public and private issuers alike in the case of financing public transportation infrastructure (TRB 2009).

Pro—Federal subsidies for bonds related to infrastructure expand the potential investment in infrastructure beyond the levels provided in direct grants. Governments have long experience with such bond programs and some states rely heavily on them.

Con—Tax exemption and tax credits reduce funding to the U.S. Department of the Treasury and thereby require additional borrowing, which increases the federal deficit. Such efforts may depress total economic growth by shifting resources away from the highest-yielding investments.

Congress has long supported subsidies for municipal bonds, and occasionally for private activity and tax credit bonds, in recognition of the benefits of attracting private investment into infrastructure. They appear to be an important part of P3 financing.

Public Loans and Loan Guarantees

Congress authorized the Transportation Infrastructure Finance and Innovation Act (TIFIA) in 1998 as part of the Transportation Efficiency Act and has subsequently reauthorized, and usually expanded, TIFIA in each surface transportation authorization (see Mallett and Driessen 2016, 11–13). TIFIA provides secured loans, loan guarantees, and lines of credit to assist P3s and others. Several features of TIFIA are attractive to issuers, especially lower interest rates available from the federal government, and to investors, especially assurance of debt repayment. TIFIA loans must receive investment grade rating and take other steps to protect the U.S. Department of the Treasury from defaults on loan repayments. Many P3s have relied, in part, on the TIFIA program. Authorization of funding for TIFIA reached an annual level of about $1 billion in 2015 under MAP-21; using a 10 to 1 approximation applied to the TIFIA program, this level of funding was expected to support more than $15 billion in total investment. Applications from states, however, quickly reached the level of funding made available (Mallett 2014, 21). Moreover, TIFIA's authorized funding was reduced to $275 million annually in direct authorization in the FAST Act. (The FAST Act, however, also allows states to draw from the two largest federal-aid programs to help fund TIFIA loans, which could, at state discretion, greatly exceed the $275 million direct authorization.)

A National Infrastructure Bank has often been proposed to provide similar services as those provided by DOT's TIFIA program, but not restricted to transportation. Congress has consistently declined to authorize a national bank, but has allowed states to set up their own state banks. Although Congress has resisted previous administrations' efforts to establish a national infrastructure bank, the FAST Act did authorize FHWA to establish an office—the Build America Bureau (BAB)—to manage two existing loan programs within the U.S. Department of Transportation and to provide states and local governments with assistance in the use of private financing and P3s. For transportation infrastructure, the BAB functions much like a national infrastructure bank would, but without the independence such a bank would have.

Pro—Direct loans and loan guarantees from the federal government can reduce borrowing costs to the issuer and risks for private and other investors and therefore expand the total investment available to transportation infrastructure.

Con—Although TIFIA loans must be investment-grade rated, they do increase the risk of (a) expanding loans and loan guarantees to projects that are not fully creditworthy and (b) possible subsequent defaults by private investors and, ultimately, losses to the U.S. Department of the Treasury.

Although the TIFIA program does involve risk, the conservative approach taken to providing loans and loan guarantees has resulted in a good track record. Of 51 active projects at the end of 2015, only 3 (6 percent) were performing below expectations regarding progress and debt repayment (U.S. DOT 2016). TIFIA, or a similar program to provide low-interest and guaranteed loans, is likely to be an important part of expanding private investment in future Interstate reconstruction and expansion.

FINANCE COMMISSION EVALUATION OF OPTIONS

The National Surface Transportation Infrastructure Financing Commission (Finance Commission) considered a wide range of potential taxes and fees associated with highway transportation, which it culled from numerous examples considered by the National Surface Transportation Policy and Revenue Study Commission, government, the American Association of State Highway and Transportation Officials (AASHTO), Transportation Research Board/National Cooperative Highway Research Program reports, and other sources (National Surface Transportation Infrastructure Financing Commission 2009). The Finance Commission's review included five extant taxes whose revenues are dedicated to the Highway Trust Fund (HTF) and more than 25 other potential taxes and fees (Exhibit 3-8 of Finance Commission report). The Commission estimated the revenue potential of these sources based on what it considered plausible, politically feasible rates. It then evaluated each of these options based on 13 different criteria such as revenue potential, sustainability, economic efficiency, justification for dedication to the HTF, political feasibility/public acceptance, cost/difficulty of administration and compliance, and various dimensions of equity (for criteria, see Exhibit J-1 of this appendix). Based on its evaluation, the Commission then classified the options as strong, moderate, weak, or inappropriate for further consideration. Following the Commission's report, AASHTO developed a matrix that provides updated, illustrative estimates of the potential revenues from many of the options the Finance Commission evaluated (see Exhibit J-2 of this appendix). The following paragraphs summarize key points from the Commission's evaluations of the options it rated as strong or moderate and provides a brief overview of the other taxes and fees considered, but largely dismissed, in the Commission's report.

Strong Options

Existing Federal Taxes Dedicated to Highway Trust Fund (HTF)

Motor Fuels Tax[9]**—**Motor fuels taxes on gasoline and diesel provide 87 percent of the revenues to the federal Highway Trust Fund (HTF), thereby meeting the criterion of revenue potential. These taxes also score well on justification for dedication to the HTF, public and political acceptance (though federal politicians have been unwilling to raise the federal tax rate since 1993), appropriateness as a federal revenue source, and ease of administration (collection costs are estimated to require about 1 percent of revenue). Because the amount of tax paid increases with distance traveled, the motor fuels tax approximates a user fee that equates the taxes paid with the amount of road use, thereby performing better than most other taxes in terms of the user beneficiary/user pay criterion. This advantage, however, is eroding as vehicles become increasingly more fuel-efficient and rely on energy sources other than gasoline or diesel fuels.

As an excise tax, the main disadvantage of a motor fuels tax is that the flat rate is undercut by inflation over time. In earlier periods, Congress raised the tax to account for inflation and demand. Between 1956 and 1993, for example, Congress increased the rate eight times, or about once every 4.6 years over a 37-year period. This compares with zero times over the most recent 25 years. Ironically, had the 1956 rate of 3 cents per gallon of gasoline been indexed to inflation, it would exceed the current rate of 18.4 cents by more than 30 percent (see Exhibit 4-1 of Commission report). An unsustainable attribute of fuels taxes is that they generate less revenue as more fuel-efficient and alternative-fueled vehicles become a larger share of the vehicle fleet. Evasion of the diesel tax has also been an ongoing issue.[10] The Commission views the motor fuels tax as having a weak linkage between efficient use and investment because the taxes do not account for the value of using scarce urban highway capacity at peak periods as would a toll or congestion fee. Nor are the revenues earned directly targeted to the corridors with the greatest demand. Furthermore, at current rates, the taxes do not reflect the environmental damages associated with the use

[9] This summary is drawn from National Surface Transportation Infrastructure Financing Commission (2009, 100–108).

[10] Typical methods of fuel tax evasion include failing to file tax information, filing false claims for refunds of fuel taxes, failing to pay the assessed taxes, filing false exemptions, and blending waste products or other untaxed products with fuel.

of motor fuels. Finally, the gasoline tax is a regressive tax—lower-income individuals spend a larger share of income on motor fuels taxes than other income groups.

Heavy Vehicle Use Tax (HVUT)[11]—The HVUT is imposed on vehicles of 55,000 gross vehicle weight (GVW) at a base rate of $100 plus $22 for each 1,000 lbs GVW in excess of 55,000 lbs, up to a maximum of $550. This tax has a strong correlation between the tax and the benefit (charges for negative impacts) given the disproportionate impact that heavy vehicles have on pavement damage. It has justifiable reasons for being dedicated to the HTF, and the benefit of a federal tax is that it establishes a consistent rate (rather than having state-by-state rates). A 50 percent increase in existing HVUT revenues would yield an additional $550 million. (In its evaluation, the Commission did not estimate the effects of a change in the structure of the tax; it only estimated the percentage increase in overall revenues from the tax.) The main disadvantages of the HVUT are that the rate would require a substantial increase in order to raise significant revenues (although the Commission views this as justifiable since it has not been raised since 1983 and its revenues have therefore been substantially eroded by inflation) and that the tax has a history of compliance and administrative issues and costs that would be compounded by a substantial increase.

Truck/Trailer Sales Tax[12]—The federal government imposes a 12 percent sales tax on the first sale of all trucks and tractors rated more than 33,000 lbs GVW. The tax applies to trailers with a GVW rating more than 26,000 lbs. Strengths of this tax include sustainability (sales tax yields increase with inflation); long history of dedication to the HTF; reasonable political acceptance; the national-level nature of the tax creates a level playing field across states; and partial recovery of the costs heavy trucks impose on the system. A 10 percent increase in the revenues from this tax would yield an additional $330 million. Weaknesses of this tax include its lack of revenue potential given that the 12 percent rate is already viewed as being fairly high; there is a lack of direct relationship between the tax paid and the amount of use; federal sales taxes are unpopular; and federal increases may reduce the ability of states to impose their own increases.

Truck Tire Tax[13]—This tax applies to truck tires with a load rating exceeding 3,500 lbs at a rate of 9.45 cents for every additional 10 lbs over 3,500 lbs. The tax helps recover the damage caused by heavy trucks; has

[11] See National Surface Transportation Infrastructure Financing Commission (2009, 73).
[12] See National Surface Transportation Infrastructure Financing Commission (2009, 71–72).
[13] See National Surface Transportation Infrastructure Financing Commission (2009, 72–73).

long been dedicated to the HTF; is viewed as cost-effective to administer; has a reasonable degree of political acceptance; and a federal tax provides an equal rate across state borders. The main disadvantages are that a large increase would be required to raise significant new revenues (a 10 percent increase in revenues from the tax would raise only $4 million in its first year); and when imposed as a flat tax it is eroded by inflation (hampering funding sustainability).

Potential New Taxes and Fees

Automobile Tire Tax[14]—A tax on automobile tires would create a counterpart to the existing tax on truck tires. It could raise a modest level of revenue (about $280 million per year based on $1 per tire in tax). Its sustainability should be good if it were to be imposed as a percentage tax like a sales tax. It could be justified for dedication to the HTF under the same rationale as the tax on heavy truck tires, and it has a moderate relationship between tax user benefit/impact. The ability of such a tax to influence efficient use of the system would be weak, however, due to a lack of a strong relationship between the incidence of the tax and use of the system. To the extent that an increase in cost contributed to delay in replacing tires, it could have a detrimental effect on safety.

Customs Duties[15]—Customs duties are imposed on all imported goods, and a surcharge could be added and dedicated to the HTF. Current duties are dedicated to the General Fund of the U.S. Department of the Treasury. A 1 percent surcharge could yield $286 million annually. The advantage of such a surcharge is that a small percentage increase yields substantial revenues, and because almost all international freight relies on highways for some part of its trip, an argument can be made for dedicating such a surcharge to the HTF. There would be little or no additional administrative cost of collection. The main disadvantages are the potential for triggering international trade disputes; the fee would do little to promote efficient system investment or use; there would be no direct relationship between the tax and any positive or negative impacts on the system and/or its users; and a surcharge would divert potential new revenues from customs duties away from the General Fund (and raise costs to consumers of imported items). Further considerations include fairness—a similar surcharge would not be imposed on outbound freight and many imported goods are duty-free under

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[14] See National Surface Transportation Infrastructure Financing Commission (2009, 78).
[15] See National Surface Transportation Infrastructure Financing Commission (2009, 87–88, 114–119).

existing trade agreements, thus the duty would fall on certain shippers and not others.

Vehicle Registration Fee[16]—A federal fee of $3 to $5 per car or truck could yield about $1 billion annually, and such a fee would be small relative to the average $185 annual fee currently imposed by the states. The advantages are that a small increase could raise substantial revenue and would be sustainable if indexed to the value of the vehicles. There would be a relationship between the fee and highway use, and the administrative cost could be small if simply added to fees states already charge. In principle, the fee could be varied to cover environmental costs of low efficiency/high polluting vehicles, but it would have to be substantially more than $3 to $5 to have any effect on purchase behavior. The weaknesses include the general unpopularity of registration fees; the lack of any efficiency incentives; potential duplication with the HVUT; and competition with the states for the same revenue base.

Container Fee[17]—A fee could be charged on inbound and outbound containers as they move through U.S. ports. A $10 fee per container could raise $500 million each year. The advantages are the ability to raise a moderate amount of new funding; moderate costs for administration and compliance; a sustainable revenue source; and a certain amount of justification for dedication to the HTF since most containers make at least part of their trips on highways. The disadvantages of this option are a lack of incentives for efficient use; potential international trade conflicts; and increased costs to consumers. There has also been little consideration of how a container fee would be implemented or how it might affect competition between U.S. ports and, particularly, Canadian and Mexican container ports. It would also treat freight differentially unless a comparable fee were imposed on non-containerized commodities.

Tariff on Imported Oil[18]—A modest tax on imported oil could raise substantial revenue—a 23 cent tax per barrel would raise $1 billion annually based on 2007 imports. Other advantages are that distillates of petroleum—gasoline and diesel—are heavily relied on by highway transportation vehicles, creating a linkage between usage and dedication to the HTF. Such a tax could also serve as an indirect carbon tax and promote U.S. energy independence. The considerable disadvantages of a tariff on imported oil

[16] See National Surface Transportation Infrastructure Financing Commission (2009, 75–76).
[17] See National Surface Transportation Infrastructure Financing Commission (2009, 86, 114–119).
[18] See National Surface Transportation Infrastructure Financing Commission (2009, 81–82).

include the fact that imported petroleum is also used for home heating, most heavily in the northern states, and a tariff dedicated to highways would be taxing homeowners (disproportionately northern homeowners) for transportation. Such a tariff could have a negative implication for trade agreements. The sustainability of the revenues would also be reduced by growing domestic production, and export, of petroleum products.

Sales Tax on Motor Fuels[19]—In some states motor fuels are subject to some or all of the statewide general sales tax, in addition to the traditional cent per gallon tax. A national sales tax on motor fuels could generate substantial revenues—a national sales tax of 1 percent on gasoline at prices/gallon ranging between $2 and $4 could raise $3.6 to $7.2 billion annually. Aside from the revenue advantages, a justification could be made for dedication to the HTF and the revenues would be sustainable for the short term. The main disadvantage of sales taxes on commodities like fuels, which vary considerably based on ever-shifting world supply and demand, is that the revenues can also vary considerably—both up and down. Furthermore, as with the excise tax on motor fuels, in the longer run the revenues will be undermined by increasing fuel efficiency and alternative fuels. Moreover, such taxes can be politically unpopular during price spikes (and even be waived or eliminated) and the incidence of the tax is unrelated to the use of particular facilities or at particular times of day.

Targeted Tolls[20]—The Finance Commission views tolling favorably, but considers this option to be most suited to local and specific circumstances (specific routes) and less applicable to addressing national road and highway funding needs. Tolls can raise substantial revenues in circumstances where sufficient traffic exists, and, once established, the revenue stream is sustainable. As discussed in Chapter 6, electronic toll collection can reduce collection costs, which can otherwise be considerable. The equity implications depend on options available to the traveler to avoid or minimize tolls.

Among its disadvantages, tolling doesn't work in low volume situations and can divert traffic to less safe routes and routes not suitable for heavy traffic. Tolling of existing routes is frequently resisted politically, whereas tolls for new routes or lanes (in the case of High-Occupancy Toll [HOT] lanes) can minimize this problem. The administrative costs are typically higher than for motor fuels taxes.

Although the Commission report notes the widespread use of tolls for motorways in other nations, it does not consider the option of tolling a

[19] See National Surface Transportation Infrastructure Financing Commission (2009, 82). Note that this option is not included in the AASHTO Matrix (AASHTO 2015).

[20] See National Surface Transportation Infrastructure Financing Commission (2009, 90–91).

network like the Interstates. The Commission does, however, encourage giving congested metropolitan areas the option of tolling urban Interstates with congestion fees, both on new and existing lanes.

Vehicle-Miles Traveled Fee[21]—The Finance Commission reviewed the concept of a vehicle-miles traveled (VMT) fee in some detail (since the Finance Commission's report was completed, mileage-based user fees [MBUFs] have become the most commonly used term to describe this concept). The Finance Commission devoted much of Chapter 6 of its *Paying Our Way* report to the topic (National Surface Transportation Infrastructure Financing Commission 2009). It ultimately recommended VMT fees as the best possible alternative to motor vehicle taxes, but noted that it was an unconventional approach that would require testing and analysis to determine its practicality and political feasibility. (Since the Commission report was issued in 2009, several pilot projects are currently under way, to evaluate various dimensions of mileage-based fees.)

Some of the advantages of a VMT fee include its substantial revenue potential (the Commission estimates it could raise as much as motor fuels taxes at rates of 0.9 cents/mi for passenger vehicles and 5 cents/mi for trucks); could be justifiably dedicated to the HTF, and would incentivize efficiency by providing a clear price signal for the extent of use. With appropriate technologies, a VMT fee could also be coupled with fees penalizing low-fuel-economy vehicles, which would reduce emissions, and charge extra for using highways at peak periods, which would improve traffic flow. The Commission's report cited a number of then-current estimates of how much a congestion fee could reduce demand and costs of adding capacity. At the time of the Commission's report, the administrative and enforcement costs of collecting a VMT fee were unknown, but have been subsequently estimated at roughly 5 to 13 percent of the collections if based on an all-electronic charging system (Kirk and Levinson 2016).

Some of the disadvantages of a VMT fee include lack of public familiarity and reticence about tolling in general; uncertainty about the optimal toll to charge; perceptions that travel is a right and should not be priced; possible inconsistencies in fees across jurisdictional boundaries (including discrimination against out-of-state travelers); and potential for route diversion by heavy trucks. The Commission recognized the opposition of the motor carrier industry, and also noted that (a) fairness argues for charging all users according to the costs they impose, (b) setting optimal prices is challenging, and (c) there is risk of discrimination against heavy out-of-state trucks in the setting of fees. Also of importance are a broad set of social

[21] See National Surface Transportation Infrastructure Financing Commission (2009, 90–91, Chapter 6).

equity concerns that would need to be addressed. Concerns about privacy are also present, including the importance of developing designs that mitigate privacy invasion. Finally, the report recognizes that technologies to support implementation require further testing and analysis.

Moderate Options

Freight Waybill Tax[22]—A tax on waybills (carrier documents describing the shipment of goods) would essentially be a sales tax on freight shipping charges. Because of the large volume and value of freight shipped by truck, such a tax could raise significant revenues, would provide a sustainable revenue stream, and could be justified for dedication to the HTF. Disadvantages include a lack of a price signal to encourage efficiency; the substantial cost and challenge of charging private fleets; the fee would be based on the value of shipments and not the costs that truck movements would have on infrastructure wear and tear; and it could result in trucks being charged more than the costs they impose.

Vehicle Sales Tax[23]—A 2.2 percent tax on new vehicles or a 1.2 percent tax on new and used vehicles could raise $1 billion annually, thus a modest tax rate for personal vehicles, modeled on the existing tax for trucks, could raise considerable resources. It should be a sustainable revenue source given the popularity of vehicles, and revenues could justifiably be dedicated to the HTF. However, the fee would have an indirect relationship between the fee and highway use; would face political opposition; would be viewed as impinging on sales taxes imposed by states and local governments, and creates administrative and compliance issues.

Harbor Maintenance Tax[24]—This tax is currently imposed on 0.125 percent of the value of imports moved through federally maintained harbors. The purpose of the collected revenues is to fund harbor maintenance conducted by the federal government, such as U.S. Army Corps of Engineers harbor activities (specially, dredging) and St. Lawrence Seaway Development Corporation operations and maintenance costs. Advantages would include its strong sustainability due to the magnitude and value of import commerce moved through U.S. ports and few additional implementation or administrative costs associated with levying the tax. Disadvantages include lack of raising substantial revenues (at its current scale), legal challenges, and, by taxing waterborne commerce, a weak connection to

[22] See National Surface Transportation Infrastructure Financing Commission (2009, 86–87).
[23] See National Surface Transportation Infrastructure Financing Commission (2009, 76–77).
[24] See National Surface Transportation Infrastructure Financing Commission (2009, 87).

highway consumption. It also excludes exports, which would raise issues about fairness.

General Fund Transfer[25]—The Finance Commission recognized the growing use of general fund transfers to the HTF, noting the considerable revenue potential, political acceptance, and ease of administration and compliance. Such an approach, however, has very weak justification for dedication to the HTF, would not promote efficient investment, and is not based on use of highways. The Finance Commission noted the competing demands for general fund revenues and questioned the sustainability of this source given the growing federal deficit.

Weak/Inappropriate Options

The Commission evaluated many other potential revenue options that it classified as not applicable/seriously flawed options for highway funding. These options are not discussed herein. They are evaluated in Chapter 3 of the Commission's report and include the following: freight ton-mile tax; driver's license surcharge; bicycle tire tax; dedicated portion of federal income tax; auto-related sales taxes; general sales taxes; vehicle inspection and traffic citation surcharge; vehicle personal property tax; windfall profits tax; petroleum franchise tax; minerals severance tax; federal tax on transit fares; and a federal tax on local parking fees.

Exhibit J-1 Finance Commission Revenue Evaluation Criteria (from Chapter 3 of Commission Report)

Revenue Potential—*the extent to which the mechanism's revenue potential at politically viable rates matches investment needs over the target time frame.*

Sustainability—*the extent to which the mechanism self-adjusts or can be adjusted easily by system operators or policy makers from year to year in order to meet needs, including but not limited to adjusting for inflation.*

Flexibility—*the extent to which the mechanism is appropriate for a wide (and potentially changing) range of investments and can be redirected to meet changing objectives, market dynamics, technology options, etc.*

Justification for Dedication of Revenues to Surface Transportation—*the extent to which it is appropriate to dedicate revenue from a particular*

[25] See National Surface Transportation Infrastructure Financing Commission (2009, 84–85).

mechanism to a specific use or set of uses, whether surface transportation generally or discrete subsets of surface transportation investment.

Public Acceptance and Legal/Political Viability—*the relative feasibility of gaining public and political acceptance of the mechanism compared with other mechanisms.*

Appropriateness for Federal Use—*the appropriateness of federal implementation, including consideration of the impact on lower levels of government if the federal government imposes or increases a certain charge or set of charges.*

Ease/Cost of Implementation and Administration—*the ease and cost to implement and administer relative to other mechanisms and to the revenue-raising potential.*

Ease/Cost of Compliance—*the extent to which the mechanism minimizes evasion and the cost of enforcement compared with other alternatives.*

Promotion of Efficient Use (Consumption) and Investment (Production)— *the extent to which the mechanism provides incentives for efficient use of the system by influencing travel choices and behavior and, in turn, efficient investment in response to the funding demand signals and based on transparent performance-based criteria.*

Creates and/or Mitigates Adverse Side Effects and Enables Charges—*the extent to which the mechanism causes and/or mitigates adverse side effects and can facilitate appropriate charges for such effects.*

User/Beneficiary Equity (User/Beneficiary Pay Principle)—*the extent to which the mechanism can be structured to charge those who directly use or otherwise benefit from the funded investment.*

Equity Across Income Groups—*the extent to which the mechanism limits costs for those who face the most difficulty in paying, including but not limited to the avoidance of regressive tax structures.*

Geographic Equity—*the extent to which the cost allocation/impact of the mechanism can be structured to match the geographic distribution of the benefit of the funded investments.*

Exhibit J-2 Matrix of Illustrative Surface Transportation Revenue Options

Existing Highway Trust Fund Revenue Mechanisms	Illustrative Rate or Percentage Increase	Definition of Mechanism/ Increase	Assumed 2014 Yield ($ billions)	Forecast Yield (2015–2200) ($ billions)
Motor fuels tax—diesel	15 cents	Cent/gal increase (approx. 10% increase)	$6.54	$41.79
Motor fuels tax—gasoline	10 cents	Cent/gal increase (approx. 10% increase)	$13.21	$78.12
Heavy vehicle use tax	50%	Increase in revenues (structure not defined)	$0.55	$3.42
Sales tax—trucks and trailers	10%	Increase in revenues (structure not defined)	$0.33	$2.19
Tire tax—trucks	10%	Increase in revenues (structure not defined)	$0.04	$0.23

Potential Highway Trust Fund Revenue Mechanisms	Illustrative Rate or Percentage Increase	Definition of Mechanism/ Increase	Assumed 2014 Yield ($ billions)[a]	Total Escalated Yield 2015–2020[a]
Container tax	$15.00	Dollar per TEU	$0.66	$4.26
Customs revenues	5%	Increase/reallocate existing revenues/structure not defined	$1.8	$11.66
Driver's license surcharge	$5.00	Dollars annually	$1.08	$6.98
Freight Bill-trucks only	0.5%	% of gross freight revenue (primary shipments only)	$3.07	$19.90
Freight Bill-all modes	0.5%	% of gross freight revenue (primary shipments only)	$3.8	$24.6
Freight charge/ ton trucks	10 cents	Cent/ton of domestic shipments	$1.17	$7.54
Freight charge/ ton all modes	10 cents	Cent/ton of domestic shipments	$1.44	$9.29
Freight charge/ ton-mile truck	0.10 cents	Cent/ton-mile of domestic shipments	$1.41	$9.15
Freight ton-mile (all modes)	0.10 cents	Cent/ton-mile of domestic shipments	$3.48	$22.52
Harbor maintenance tax	25%	Increase/reallocate existing revenues/structure not defined	$0.43	$2.79
Imported oil tax	$2.50	Dollars/barrel	$5.76	$37.28

Exhibit J-2 Continued

Potential Highway Trust Fund Revenue Mechanisms	**Illustrative Rate or Percentage Increase**	**Definition of Mechanism/ Increase**	**Assumed 2014 Yield ($ billions)**[a]	**Total Escalated Yield 2015–2020**[a]
Income tax—business	1%	Increase/reallocate existing revenues/structure not defined	$2.79	$18.06
Income tax—personal	0.5%	Increase/reallocate existing revenues/structure not defined	$6.70	$43.36
Diesel motor fuel tax indexed to CPI	—	Cent/gallon excise tax	—	$5.22
Gasoline motor fuel tax indexed to CPI	—	Cent/gallon excise tax	—	$10.87
Oil, gas, and minerals receipts	25%	Increase/reallocate existing revenues/structure not defined	$2.20	$14.25
Registration fee—Electric light duty vehicles (LDVs)[b]	$100	Dollar annually	$0.01	$0.06
Registration fee—hybrid LDVs	$50	Dollar annually	$0.17	$1.12
Registration fee—all LDVs	$15	Dollar annually	$3.57	$23.11
Registration fee—trucks	$150	Dollar annually	$1.63	$10.54
Registration fee—all vehicles	$20	Dollar annually	$4.98	$32.21
Sales tax—auto-related parts and services	1.0%	Percentage of sales	$2.32	$15.04
Sales tax—bicycles	1.0%	Percentage of sales	$0.06	$0.38
Sales tax—diesel	7.6%	Percentage of sales (excluding excise tax)	$9.65	$62.50
Sales tax—gasoline	5.6%	Percentage of sales (excluding excise tax)	$24.05	$155.66
Sales tax—new LDVs	1.0%	Percentage of sales	$2.41	$15.61
Sales tax—new and used LDVs	1.0%	Percentage of sales	$3.46	$22.40

continued

Exhibit J-2 Continued

Potential Highway Trust Fund Revenue Mechanisms	Illustrative Rate or Percentage Increase	Definition of Mechanism/ Increase	Assumed 2014 Yield ($ billions)[a]	Total Escalated Yield 2015–2020[a]
Tire tax—bicycles	$2.50	Dollar per bicycle tire	$0.08	$0.53
Tire tax—LDVs	1.0%	Of sales of LDV tires	$0.33	$2.12
Transit passenger mile traveled fee	1.5 cents	Cents/passenger mile all transit modes	$0.84	$5.45
VMT fee—all LDVs	1.0 cent	Cents/vehicle-mile traveled on all roads	$27.12	$175.58
VMT fee—trucks	4.0 cents	Cents/truck-mile traveled on all roads	$10.93	$70.73
VMT fee—all vehicles	—	Cents/vehicle-mile traveled on all roads	$38.05	$246.31

NOTE: LDV = light-duty vehicle; VMT = vehicle-miles traveled.
[a]Base annual yield escalated using CPI-U.
[b]LDVs are vehicles that weigh less than 10,000 lbs.
SOURCE: AASHTO 2015.

AN INTERNATIONAL OVERVIEW OF MOTORWAY FUNDING AND FINANCE IN INDUSTRIALIZED DEMOCRACIES

Different models exist internationally for paying for intercity highways: government funding from user taxes; government funding from general revenues; and financing using borrowed funds that are repaid by either tolls, distance-based fees, or from general revenues. The United States uses the first approach, which is increasingly rare around the world, perhaps because of its governance structure. This overview of international practice is followed by brief descriptions of motorway funding and finance programs in selected countries. This appendix is a high-level overview. There are many subtleties, complexities, and ongoing changes in the funding and financing arrangements of individual nations that cannot be fully captured in a short document such as this.

International Comparison

Nations vary widely in how they plan for, manage, and fund or finance their motorways. As described next, four important distinctions apply: (a) the role of the national government in decision making about motorways, (b) the sources of funds and whether they are dedicated specifically to highway construction and maintenance, (c) reliance on direct user charges such as tolls or distance-based fees, and (d) the role of supplemental loan programs.

National Role

In terms of governance, the United States is most similar to Australia and Canada. All three nations have a central government that helps fund motorways, but depend on states or provinces to make decisions about, plan for, build, own, and maintain highways. Perhaps for this reason, these countries have similar funding arrangements—various forms of supplemental national funding—to encourage and facilitate construction and maintenance of an interconnected system of motorways. In western Europe, Japan, and New Zealand, the national governments take a much more centralized role in planning, constructing, and funding motorways and are somewhat more likely to rely on tolls or distance-based fees, though not exclusively. For example, although more centralized than the United States, in some western European countries, such as France, Germany, and Italy, regional governments play a role in developing and funding motorways, albeit usually with funds provided by the national government.

Dedicated Funding

In northern Europe, Australia, and Canada, motorways are funded by general revenues, although Australia and Canada formerly relied on dedicated taxes and fees from motor fuels taxes and other user charges and several European countries have begun to impose distance-based user fees on heavy trucks using motorways. As described below, motorways in southern Europe are more likely to be tolled motorways, but Spain and other countries also have national systems of un-tolled motorways funded by their central governments from general revenues and, to a lesser extent by grants and loans from the European Union (EU).

In the United States, the principal source of funding for the Interstate System has come from fuel taxes and other user fees at the federal and state levels, the revenues from which are dedicated to highway funding. At a time when vehicle-miles of travel were increasing sharply and political leaders were willing to raise motor fuel taxes to keep up with inflation, this approach provided ample funds for Interstate highway construction. Throughout most of western Europe, fuel taxes, which are considerably higher than in the United States, are general taxes whose revenues flow to national treasuries and are not typically dedicated to highway funding. (Road user charges and associated taxes and fees generate more revenues for European nations than are spent on roads [Gomez and Vassallo 2014].) Australia and Canada, and, to a much lesser extent, Japan, have also relied on dedicated motor fuel taxes and other user fees to fund motorways when building their systems. All three of these nations, however, have ended this practice and now rely on general fund appropriations for non-tolled highways. The United States is one among a small number of other counties, such as the Netherlands, New Zealand, and Switzerland, that rely on trust funds for highways at the national level that are funded through road user charges.

Direct User Charges

Tolls—About 40 percent of western European motorways[26] are tolled for cars and trucks (see Table J-1) (not including heavy truck mileage fees that apply in Austria, Germany, and Switzerland as described in the next section) and almost all of Japan's expressways are tolled. By way of comparison, about 7 percent of the U.S. Interstate system is tolled (Kirk 2017). Western European countries have roughly 66,600 kilometers of motorways, whose design is roughly comparable to that of the U.S. Interstate System (see Table J-1). In those same nations, about 43,000 kilometers of main highways are operated as toll roads, most of which are motorways, but not exclusively. Over the past decade, the extent of tolled roads has increased 18 percent across nations listed in Table J-1.

France, Greece, Italy, Japan, Portugal, and Spain have been the most dependent on tolls to finance their motorways. Most toll roads in these nations are now operated by private concessionaires, but, with the exception of Spain, where concessionaires have always been private, most were formerly public toll authorities. (Japan is a bit of a special case, as its commercial toll authorities are not privatized in the western sense.) In most other western European countries, the toll authorities tend to be public and there is little reliance on tolls beyond high-cost tunnels and bridges. This tendency is changing, however, in response to the EU directive on pricing of heavy truck use of motorways, as discussed in the next section.

In France, Italy, Japan, and Portugal private concessionaires manage three-quarters or more of motorways; that share drops to about one-quarter in Spain (Albalate et al. 2009). Privatization of toll authorities in France, Italy, and Portugal since 2000 has had mixed results. The privatization wave in Europe was partly due to EU directives for nations to reduce debt. In response, toll authorities were sold to private investors, but many private toll roads retained favorable loans, loan guarantees, and other public subsidies (Albalate et al. 2009). The wave of privatization has been accompanied by increased regulation of private concessionaires, including regulations applying to toll increases. It has also sparked consolidation of the industry as private concessionaires from multiple countries have been

[26] Analogous to U.S. Interstates.

TABLE J-1 Motorways and Tolled Roads in Selected Nations

Country	Motorways[a] (km)	Tolled Main Roads[b] (km)	Increase in Tolled Road Length (km) 2006–2016 (%)
Austria	1,719	2,199	6.6
Belgium[c]	1,763	1.4	—
Denmark	1,216	34	0
Finland	810	—	—
France	11,552	9,137	10.1
Germany[d] (trucks only)	12,917	15,276	—
Greece	1,558	1,843	101.0
Italy	6,751	6,003	6.3
Japan[e]	11,000	14,000	—
Netherlands	2,678	24	20.0
New Zealand (diesel vehicles only)[f]	200	10,916	n/a
Norway	392	911	36.0
Portugal	3,065	2,943	91.6
Spain	14,981	3,404	9.8
Sweden	2,057	—	—
Switzerland[g] (trucks only)	1,419	18,013	n/a
United Kingdom	3,760	42	0.0
United States[h]	72,243	3,838	16.8

[a]Extent of toll roads as of end of 2013. Data limited to members of the EURF (European Union Road Federation 2017).

[b]Note that tolled roads do not necessarily correspond with motorways. Also note that the extent of tolled routes is available mostly for members of the association. There may be other tolled kilometers managed by toll authorities or nations that are not ASECAP members (ASECAP 2017).

[c]Belgium statistics as of 2009, the last year of ASECAP membership.

[d]Truck emission tolls applied to motorways and other principal roads.

[e]See section above on Japan for data sources.

[f]Trucks and cars using diesel fuel in New Zealand pay a per-mile fee based on vehicle class, weight, and distance traveled based on odometer readings. National highway mileage from International Road Federation (2014).

[g]Switzerland has electronic truck tolls on its motorways as well as all other Swiss roads. Passenger cars are required to have sticker that is paid for annually for a nominal fee (40 Swiss Francs). Motorway and national highway mileage from International Road Federation (2014).

[h]The increase in toll length in the United States are from 2007 to 2017 (FHWA n.d.-b).

bought and combined by investors.[27] As noted in the section that follows on individual countries, the financial crisis of the late 2000s has complicated the financial viability of some toll roads in Spain and Portugal. Japan also financed its expressways through public toll corporations, which it subsequently re-organized into more commercialized, but still publicly owned, enterprises when some of the corporations were unable to collect sufficient tolls to repay their debts.

In Australia, Canada, and New Zealand tolls on motorways are rare. Australia has seven intra-urban tolled motorways of 20 to 40 kilometers in length (about 206 kilometers) that operate in New South Wales, Victoria, and Queensland, but no interstate tolled motorways (Australian Government Department of Infrastructure and Regional Development 2016). Canada has three tolled motorways, also intra-provincial, which represent far less than 1 percent of its motorways. New Zealand has three short tolled highways, but diesel-powered commercial vehicles and passenger vehicles pay distance-based road user charges, as described next.

Distance-Based Fees on Trucks

In line with an EU directive encouraging nations to charge trucks for using main highways (European Parliament 2017), truck distance-based fees are imposed on more than 35,000 of Western Europe's highways in Austria, Germany, and Switzerland (see Table J-1). These fees are based on trucks weighing more than 3.5 tons and the distance traveled, and travel is tracked and fees charged electronically. In Germany, these truck fees apply to motorways and most other principal highways[28] and in Switzerland they apply to all roads (Luechinger and Roth 2016). Also, unlike motor fuel taxes and other user fees, the revenues earned from these truck distance charges are dedicated to transportation (Doll et al. 2017). As countries located in the middle of Europe, these nations carry a considerable share of through truck traffic, which perhaps explains their choice of this funding mechanism. A similar approach to truck distance-based fees was rejected in France due to opposition from truckers (Todd 2017). In addition to tolled highways, Belgium, Denmark, Luxembourg, the Netherlands, and Sweden require

[27] As of May 1, 2018, Autostrade in Italy was purchased by the Benetton Group, which changed the name to Autostrade per l'Italia, and combined it with Benetton's Atlantia. Italy's other main concessionaire is the Gavio Group. In France, the main concessionaires are Eiffageup, Vinci, and Abertis, the latter of which is also the most important concessionaire in Spain and Portugal. Atlantia, together with Hochtief from Germany, subsequently acquired Abertis, transforming Atlantia into a world leader. (Information provided by Remy Cohen, Cohen & Co., Milan, in private correspondence.)

[28] Although the funds are used to maintain motorways, the highways were built with other funds before tolls were imposed. Tolls are imposed on heavy trucks consistent with EU policy.

trucks to purchase vignettes[29] to operate on their motorways (Gomez and Vassallo 2014). Vignette systems are time-based rather than distance-based, but can serve as precursors to electronic charging systems, as used in Austria, Germany, and Switzerland. Commercial vehicles using diesel fuel in New Zealand have paid a road user charge based on vehicle weight and distance traveled since 1977 (see reporting in next section on selected nations). Unlike many toll programs, which generate revenues to repay loans related to specific highway segments, distance-based fees provide revenues for general motorway reconstruction and maintenance.

Supplemental Loan Programs

The EU and the European Investment Bank (EIB) have provided supplemental sources for co-funding and financing major highways and motorways in Europe providing cross-continental routes. A variety of EU programs designed to connect the infrastructure of the EU across member nations have been important partial sources of funding for roads in general as well as for loans and loan guarantees mostly provided by the EIB. These sources are estimated to have provided nearly 47 billion euros for roads for EU member states between 2000 and 2013 (Pantelias et al. 2010, Table 1).[30] The role of the EIB was particularly important during the financial crisis when private funding for infrastructure was in limited supply. Since 1990, the EIB has encouraged use of P3s through co-funding and partial financing of individual motorway improvement projects in Belgium, France, Germany, Ireland, the Netherlands, Norway, and the United Kingdom (European Investment Bank 2018). These loans are typically, though not exclusively, repaid by the national governments through availability payments funded from general revenues.

Funding and Financing of Motorways in Selected Nations

Austria

In 1982, Austria created a government-owned company to plan, finance, construct, and operate a national motorway system of 2,000 kilometers; in 1997 the company was given authority to impose direct user charges.[31] Previously, motorways were funded out of general revenues, but relatively

[29] Vignettes are time-based flat fees that permit a vehicle user to operate in a specific area or on specific roads. They are typically displayed as stickers on the vehicle.

[30] This source estimates that motorways received about □9 billion in EU cohesion funds between 2000 and 2013.

[31] This paragraph was drawn from Rothengatter (2005).

few kilometers were constructed after World War II. The Austrian system consists of a time-related vignette (10 days, 1 month, or annual stickers only) for vehicles weighing less than or equal to 3.5 tons and motorcycles and a distance-related electronic toll for vehicles weighing more than 3.5 tons.[32] Plans are currently in development to switch to electronic tolling for passenger vehicles based on license plate readers. Fees for vehicles with a maximum gross vehicle weight exceeding 3.5 tons are collected electronically via a free flow, multi-lane, digital short-range communications (DSRC) system.

Australia

Australia's federal structure and highway program is similar to that of the United States. The federal government provides funding to support motorways and other roads constructed and maintained by the states and local governments (The Law Library of Congress 2014). The federal government ended dedication of federal fuel and heavy vehicle taxes and other user fees to road construction in 1959, but continues to fund programs supporting roads maintained by states and local governments, including a program focused on state highways of national significance. Beginning in 2014, the federal government began expressing interest in placing greater reliance on toll roads, but to date none are intercity motorways. As of 2016, Australia had 16 tolled facilities, seven of which are on intra-urban highways and all others of which are on tunnels and river and harbor crossings (Australian Government Department of Infrastructure and Regional Development 2016). Between 2010 and 2016, the number of toll operators declined from nine to six. One toll operator, Transurban, dominates the market with 73 percent of toll revenues.

Beginning in 2014, the national government began promoting the concept of asset recycling, through which states that sold or leased infrastructure assets to the private sector would receive 15 percent federal funding on top of the payout received if the state reinvested the funds in greenfield infrastructure. The concept has been proposed for consideration in the United States (Varne and Kline 2017). The Australian program ended in 2016, before the available funds were fully allocated, apparently due to fundamental issues such as that income-generating assets were sold to finance new investments that did not generate income (Quiggen 2017). There is a recent proposal within Australia for reviving it (McIlroy 2018).

[32] Austrian national report to ASECAP Study and Information Days, Madrid, May 23–25, 2016 (ASECAP 2016).

Canada

Canada's constitution places responsibility for highways with its provinces and territories (The Law Library of Congress 2014). Canada's federal structure is analogous to that of the United States, but the national government is not as involved in the country's intercity highways. The federal government has historically provided supplemental funding for highway infrastructure on an ad hoc rather than long-term basis; this supplemental funding for provincial and territorial highways has been typically provided on a cost-share arrangement for specific routes. The national government does collect motor fuel taxes and heavy vehicle taxes, but these funds are not earmarked to highways. Provinces also collect motor fuel, vehicle registration fees, and other taxes, but, with the exception of Nova Scotia, these funds are not dedicated for roads.

The Canadian National Highway System (NHS) is made up of more than 38,000 lane-kilometers, about 73 percent of these lane-kilometers are on the "core" system of intercity highways (Transport Canada 2017, 23). The remainder are feeder routes and northern/remote routes. Canada has about 17,000 kilometers of motorways (International Road Federation 2014, Table 2.1). Only three intercity routes are tolled. The longest is the 407 Express Toll Route, a 137.8-kilometer all-electronic toll highway within Ontario. Also tolled is a 45-kilometer stretch in Nova Scotia and a short, 10-kilometer highway that connects two other highways in Ontario.

France

France embarked on a concerted national program to build motorways beginning in 1960, which had grown from 170 kilometers in that year to 10,400 by 2005, roughly three-quarters of which were tolled.[33] France relied on public corporations collecting toll revenues throughout this period; tolled motorways also received considerable public subsidy, and loans were typically guaranteed by the nation. In 2003, as France was beginning to privatize its concessionaires, public funding for tolled roads nearly matched expenditures of toll revenues for motorway construction, operation, and maintenance.

France now has an extensive set of tollways operated by several concessionaires that includes most of the nation's principal intercity highways. Payments are made at toll plazas by any mechanism (electronic reader, credit card, check, cash).[34] After 2000, France privatized its seven largest, formerly public corporations, but the government retains ownership of the

[33] The paragraph on France is drawn from Fayard et al. (2005).
[34] French national report to ASECAP Study and Information Days, Madrid, May 23–25, 2016 (ASECAP 2016).

assets and regulatory control over their operations (Bonnafous 2015). As part of the sale, most public subsidies were withdrawn and the toll roads were allowed to increase tolls, which one analyst suggests are on conditions favorable to investors (Cave 2014).

In addition to its existing toll roads, which affect passenger cars and trucks alike, the French parliament agreed in 2013 to follow EU policy regarding charging a fee on trucks in excess of 3.5 tons on other, non-tolled national highways (10,000 kilometers) and local roads (5,000 kilometers), with funds received dedicated to transportation improvements (Ptolemus Consulting Group 2015). In response to violent protests in Brittany and protests in other regions, the scope of the proposal was reduced in 2014 to 4,000 kilometers and was subsequently abandoned.

Germany

Motorway construction in Germany, which began before World War II, has been funded from national general tax revenues. Motorists currently pay a fuel tax and ecological tax, as well as a Value Added Tax (VAT) on the fuel tax.[35] Motorists pay more such taxes for use of roads into the nation's general fund than are invested in the national road system. With limited exceptions, motorists' taxes have not been earmarked for transportation purposes. Around 2000, Germany began planning to charge tolls on heavy trucks to both shift some truck traffic to rail and water modes and to provide funds to maintain major highways, railroads, and waterways.

Located in the middle of the EU, Germany's motorways and main highways are used heavily as through routes for trucks. Since 2005, the German government has been implementing the 1999 EU Directive permitting distance-based charges on all trucks (at or above 7.5 tons) for its entire motorway network and main highways.[36] Most German highways used as truck routes are now covered by the fee. Part of the rationale for the charge is to encourage freight to shift to freight railroads. Ninety-four percent of revenues are collected via a system of on-board units (OBUs) that are tracked by satellite. European trucking firms using German roads have registered more than 950,000 OBUs. Truck tolls can also be paid at toll stations and by direct billing. Although the German system tracks travel comprehensively and accurately, and with little evasion, the administrative costs are fairly high—roughly 13 percent of revenues earned (GAO 2012, 27). Light-duty and passenger vehicles do not pay tolls except for use of two tunnels.

[35] The paragraph on Germany is drawn from Rothengatter (2005).

[36] This paragraph is drawn from German national report to ASECAP Study and Information Days, Madrid, May 23–25, 2016 (ASECAP 2016).

Italy

Italy began its motorways development with toll roads in the 1920s, but these failed.[37] When motorway development began anew in the 1950s, Italy again relied on government-owned concessionaires. By 1970, Italy had almost 4,000 kilometers under concession. Concessionaires were financed by toll revenues and state subsidy (roughly one-third or less before 1960 and up to 50 percent afterward).

Italy's tolled network, which represents most of its motorways, extends the length of the country along both coasts, but is more heavily concentrated around Rome and in the northern third of the country.[38] Tolls can be paid electronically or by other means at toll plazas. Tolls apply to both light-duty and heavy-duty vehicles. Traffic on tolled roads fell sharply after the 2008 financial crisis and remained 10 to 15 percent below the 2008 peak as of 2015. Italy's toll roads were privatized around 2000. Autostrade, which controlled about 60 percent of Italy's roads under concession in 2009, was a public agency until 1999 (Albalate et al. 2009).

Japan

The national government of Japan began a program of national expressways in 1956, which totals about 10,000 kilometers.[39] These intercity highways were designed, constructed, and maintained by public corporations, which borrowed funds that were to be repaid by tolls. The public corporations also received low-interest loans and other subsidies (The Law Library of Congress 2014, 60–66). The four corporations were reshaped into six government-owned, commercially oriented enterprises in 2005 when it became clear that more kilometers of expressways had been built than could be repaid using tolls. A debt repayment organization was established to lease the government's expressways to the new enterprises. As a government-owned organization, it is able to borrow at government rates and lend funds at low or no interest to the new enterprises. It is repaying the outstanding loans of the former corporations using toll revenues provided by the lessees.

Japan plans to build about 14,000 kilometers of intercity highways, which will mostly be the tolled expressways described above, but it will also include about 2,500 kilometers of national highways that are managed by the national government. These highways are funded, in part, from national motor fuels taxes and other user fees that went into a dedicated fund for

[37] The paragraph on Italy is drawn from Greco and Ragazzi (2005).

[38] This paragraph is drawn from Italian National report to ASECAP Study and Information Days, Madrid, May 23–25, 2016 (ASECAP 2016).

[39] This paragraph draws heavily from Vasallo (2008).

Japanese roads and highways. Dedication of user fees for highways at the national level ended in 2009. Japan now relies on the national general fund for its national highways.

The Netherlands

Motorways in The Netherlands are funded from a variety of motor fuel taxes, registration fees, sales taxes, heavy-vehicle taxes and other fees that flow to a national fund for infrastructure, which is managed at the national level (The Law Library of Congress 2014, 69–72). The country has about 2,000 kilometers of motorways and another 1,000 kilometers of expressways that are also high-speed routes but are not built to motorway standards (Wikipedia n.d.). Motorways and expressways are not tolled, but the Netherlands has joined in a vignette program for heavy trucks with neighboring countries. The Netherlands case is of interest because its dedication of user taxes, as in the United States, and because in 2009 the national government gave serious consideration to abolishing the gasoline tax (more than $1 U.S./liter) and replacing it with a distance-based fee. This proposal, however, was withdrawn following a change of governments (Sorenson 2013).

New Zealand

New Zealand began its program of national road building in the 1920s.[40] The New Zealand Transport Agency administers roughly 11,000 kilometers of state roads, about 200 kilometers of which are motorways. Three roads are tolled. In general, New Zealand relies on fuel tax and other user charges to pay for state roads and motorways, the revenues from which are dedicated to a national fund for investing in roads and highways. Most passenger vehicle users pay for highways through motor fuels taxes, but vehicles that rely on diesel fuel pay a road user charge based on distance traveled. (A motor fuels tax on diesel is not imposed because a substantial share of New Zealand diesel use is off road, primarily in agriculture.) The fee for trucks over 3.5 kg includes an assessment based on the lesser of the vehicle's gross mass (fully loaded) or its maximum allowable loaded mass. Diesel-fueled light-duty vehicles (LDVs) weighing less than 3.5 kg must buy distance licenses in increments of 1,000 kilometers. New Zealand is among a handful of nations that charge commercial vehicles based on the distance traveled and weight and its system. In place since 1977, New Zealand has a unique approach to implementation and enforcement (GAO 2012). Enforcement of LDV compliance is carried out by spot-checking odometer

[40] Unless otherwise specified, information cited is taken from NZTA (n.d.).

readings by police, but they have no way of knowing whether the odometer is operating properly. Commercial vehicles, in contrast, must use a specified technology to ensure accuracy.[41] GAO's (2012) report cites a fee of roughly 43 cents (U.S.) per mile for a 40,000 lb 3-axle truck and 35 cents (U.S.) for a vehicle of similar weight that has five axles. Enforcement of commercial vehicle compliance is carried out manually at inspection stations. Although the overall cost of manual enforcement is relatively low compared with revenues earned through the system (about 2.5 percent), roughly 4 percent of commercial vehicle revenues are estimated to be lost due to evasion.

Portugal

Portugal's motorway network, 92 percent of which is tolled, is managed by 17 different concessionaires.[42] Tolled operations began in 1972 and have been expanded by the government over time. Some roads were built and maintained by concessionaires that were paid shadow tolls (road users not charged directly) by the national government. Subsequently, seven roads operating under shadow tolls were shifted to direct tolls because of the cost burden imposed on the national government (Fernandes and Viegas 2005). In 2007, Portugal shifted to operating its national road authority as a public agency to a private concessionaire, which, in turn, manages all other sub-concessionaires. New routes were opened exclusively with electronic toll collection. Most of the country's motorways are operated by private concessionaires, but, as of 2013, several private toll roads were short of sufficient traffic to remain viable.

Scandinavia

The Scandinavian countries of Denmark and Sweden have mostly relied on general funds for highways, whereas Norway has also relied on tolls for major tunnels and bridges as well as for highways.[43] Denmark has tolls on two long road/rail bridges linking Denmark's two largest islands and mainland with Sweden. Its motorways are otherwise un-tolled for passenger vehicles. Sweden's highways and motorways are mostly publicly funded, with the exception of the tolled bridge it shares with Denmark. Sweden and Denmark, in partnership with Luxembourg and the Netherlands, have fairly recently partnered on a vignette for trucks in excess of 12 tons for motorway use in all four nations (Skatteverket n.d.). Norway has relied

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[41] The following sentences are from GAO (2012).
[42] Portuguese national report to ASECAP Study and Information Days, Madrid, May 23–25, 2016 (ASECAP 2016).
[43] This paragraph draws from Bråthen (2005).

on tolling for many projects, but unlike some southern European nations, Norway expects toll projects to be self-funded by tolls (without public subsidy). Road users in Denmark and Norway pay far more in fuel, vehicle, and license taxes (which are not dedicated to road funding) than are spent on motorways and highways. (Comparable statistics for Sweden not available from primary source for this paragraph.)

Spain

Spain has a large network of national highways, about 15,000 kilometers, compared to about 3,500 kilometers of privately operated toll roads (see Table J-1). Although most national highways were funded publicly starting in the 1970s, Spain relies on private companies to build and operate toll roads that the public sector could not afford to build (Acrete et al. 2009). Up until 1980, almost 80 percent of motorways were tolled, but by 2003, this share had dropped to 20 percent (Bel and Fageda 2005). In response to the 2007–2008 financial crisis, traffic on toll roads that had peaked in 2006 fell sharply after 2007 (about 30 percent) and, had barely recovered to the 2006 peak by 2016.[44] The Spanish network of un-tolled roads offers alternatives to tolled roads, which subsequently suffered from inadequate traffic during Spain's financial crisis. As of 2016, low traffic had forced nine concessionaires, representing more than one-fifth of the tolled roads, into bankruptcy proceedings (Ptolemus Consulting Group 2015, 80–83). As of 2016, eight concessionaires were in the final stages of bankruptcy. Spain proposes to tender the routes managed by these concessionaires again and continue to rely on tolls.[45]

Switzerland

Following a national vote taken in 1958, the Swiss embarked on a program of building motorways exclusively funded publicly.[46] By the end of 2002, the network had reached more than 1,300 kilometers (almost its current extent). The main sources of revenues have been the fuel tax and a heavy vehicle vignette (which turned into a distance and weight-based fee) that are dedicated to this purpose. As a nation at the crossroads of Europe, Switzerland had attempted to restrict heavy truck traffic by weight (up to 28 tons) and to night hours in an effort to shift cross-national freight to rail. After lengthy negotiation with the EU, in 2002 Switzerland lifted its restrictions on heavy trucks (to 40 tons) and imposed heavy vehicle use

[44] Spanish national reports ASECAP (2015) and ASECAP (2016).
[45] Personal communication, Jose M. Vassallo.
[46] This paragraph draws from Rudel et al. (2005).

tolls with a system comparable to, but with higher tolls than, Austria's and Germany's. A recent paper finds a modest decline in heavy truck traffic and reductions in vehicle emissions (Luechinger and Roth 2016). Unlike these nations, Switzerland's fees apply to truck use of all roads. The revenues from these tolls flow to a fund dedicated to the transalpine railway infrastructure and other major rail improvements.

United Kingdom

The United Kingdom began its highway program in the 1920s with the expectation that road user taxes would be dedicated for the purposes of building and maintaining roads, but this principle was severed in practice and subsequently abandoned.[47] Although almost all highways have been funded with public funds, road users pay more in fuel and other taxes than is spent on highways. The only tolled section of motorway in the United Kingdom occurs on a 42-kilometer section of the M6 motorway.[48] About 540 miles of motorway are financed by shadow tolls (Albalate et al. 2009). A few motorway improvements financed through the EIB are repaid through availability payments.

Table J-2 also summarizes the current funding mechanisms and the extent of their motorway network for a selected group of industrialized nations, including the United States.

MOTOR FUEL AND PER-MILE RATES REQUIRED TO RAISE FUNDS NEEDED TO PAY FOR INTERSTATE MODERNIZATION BY 2036

As described in Chapter 5, the cost to modernize the Interstates ranges between roughly an additional $20 billion to $50 billion per year beyond the current investment. This section estimates what would federal (i) motor fuel tax rates or (ii) per-mile fees need to be to increase the revenue by $20 billion annually.

Estimated Future Rates

In order to raise a fixed amount of funds from highway users in the future, the rates to be paid depend on the estimated amount of future VMT, fuel economy, and number of vehicles being operated on the road.

[47] This paragraph draws from Mackie and Smith (2005).

[48] UK national report to ASECAP Study and Information Days, Madrid, May 23–25, 2016 (ASECAP 2016).

TABLE J-2 Current Funding Mechanism for Motorways in Selected Nations

Country	Motorways, mi. (km)	Current Funding Mechanism
Austria[a]	1,068 (1,719)	A public corporation imposes direct user fees for motorways.
Belgium[b]	1,095 (1,763)	The Belgian government funds motorways from general revenues.
France[c]	7,178 (11,552)	Concessionaires build, operate, and maintain approximately 75 percent of the French motorway network. A public corporation finances those private sector motorway operators for motorway construction. For publicly operated and maintained motorways, general tax revenues supply the funding.
Germany[a] (trucks only)	8,026 (12,917)	The German federal government appropriates general revenues for motorways and federal roads. The government levies taxes on gasoline, motor vehicles, and truck traffic for funding.
Italy[d]	4,195 (6,751)	Italy generally funds its motorways through tolling.
Japan[e]	6,835 (11,000)	Six private toll road operators build and manage Japan's motorway system. A portion of the revenues from tolling are paid to a public corporation that controls the leases for the motorways. The public corporation in turn provides financing to the toll road operators for new construction. For motorways directly managed by government, the national government pays 75 percent and prefectural governments pay 25 percent of the construction costs.
Netherlands[e]	1,664 (2,678)	The Netherlands funds its motorways through several taxes, including a motor vehicle registration fee and a tax on heavy trucks. In addition, the Netherlands has authorized the use of public–private partnerships to fund motorways.
Portugal[c]	1,905 (3,065)	Portugal relies predominantly on tolling to fund its motorways, which are operated by more than a dozen concessionaires.

TABLE J-2 Continued

Country	Motorways, mi. (km)	Current Funding Mechanism
Spain[e]	9,309 (14,981)	Although the 2008 financial crisis caused several concessionaires to enter bankruptcy, Spain maintains its reliance on toll revenue collected by concessionaires to fund the motorway network.
Sweden[e]	1,278 (2,057)	Sweden funds its public network of motorways through state and local taxes.
United Kingdom[e]	2,336 (3,760)	The UK motorway network predominantly relies on revenues from the fuel and other taxes for building and maintenance. Shadow tolls finance a limited portion of the motorway network.
United States[f]	49,455 (79,590)	Revenues for Interstate and other federal-aid highway funding derive from federal motor fuel taxes and taxes on heavy trucks and truck tires.

[a]Federal parliamentary republic.
[b]Federal parliamentary democracy under a constitutional monarchy.
[c]Semi-presidential republic.
[d]Parliamentary republic.
[e]Parliamentary constitutional monarchy.
[f]Constitutional federal republic.
SOURCES: Acosta 2014; Biatour et al. 2017; World Road Association n.d.

Motor Fuels Tax Revenues

The amount of revenue to be raised from motor fuels taxes is calculated by multiplying the projected number of gallons of gasoline or diesel fuel consumed times the tax rates appropriate for light-duty vehicles (LDVs) (gasoline) and straight and combination trucks (diesel).[49] With a 20-year modernization effort in mind, the year 2026 is used to illustrate potential future rates necessary to raise the desired amounts. Projected rates by 2026 would allow time for rates to be phased in over time, for a construction program to ramp up, and, in the case of per-mile fees, for necessary electronic charging infrastructure to be installed. The year 2026 is also 10 years out from the baseline year for which aggregate statistics are available

[49] To simplify, all medium-duty trucks are assumed to use diesel.

for LDVs and trucks on VMT, fuel economy,[50] and number of registered vehicles (FHWA 2017, Table VM-1).[51]

Mileage-Based User Fee Revenues

The amount of revenue to be raised from a mileage-based fee begins with the amounts being paid through motor fuels taxes, as calculated above, but is limited to VMT on the Interstates. The per-mile rates needed to raise the needed funds are calculated based on projected VMT and vehicles operating and the rates needed at future traffic levels to generate the amounts required.

Estimated Mileage Traveled

To calculate future VMT for LDVs and medium- and heavy-duty trucks, this analysis used the committee's annual VMT growth rates (0.75 percent, 1.5 percent, and 2.0 percent). VMT, registered vehicle, and average miles per gallon (MPG) estimates from *Highway Statistics 2016*, Table VM-1 are used as the baseline year, which are projected for LDV, straight truck, and combination trucks through 2026. Note that for the calculations in this analysis, the VMT traveled by classes of vehicles is for use of all roads and not just the Interstates since it is not possible to charge a different fuel rate for use of different classes of local roads and highways. Thus, the money raised for the Interstates would have to be raised from users of all classes of roads and highways.

Estimated Fleet Average Fuel Economy

For LDVs, the Energy Information Administration (EIA) has projected fleet average fuel economy from 2016 to 2050 (EIA 2018) (although the analysis described in this document only uses EIA projections for 10 years out since it estimates revenues needed and rates required in 2026). For future truck fuel economy, the analysis relies on a recent paper by Burke and Zhao (2017), which simulates future medium- and heavy-duty truck MPGs for 2030 and 2050 and compares them to baseline EPA projections. These simulations were conducted for selected medium- and heavy-duty trucks. Rather than use the estimated truck fuel economy estimates from

[50] Fuel economy only considers gas/diesel vehicles, it does not include phase-in of all electric vehicles.

[51] Because VMT, MPG, and the number of vehicles increase over time, the amount of funds raised in a given year will constantly change. In the early years revenues will be below the target and in later years, the revenues will be above the target. Picking a middle year provides an estimate of the median revenues brought in.

Burke and Zhao's (2017) paper, the average annual percentage changes in MPG from their simulations were applied to straight truck and combination truck fleet MPG beginning in 2016 from FHWA (2017, Table VM-1). The rates of change in this calculation of improved fuel economy for trucks are at or below those for LDVs, and since class 8 tractors used in combination trucks in long-distance trucking turn over about every 4 to 6 years (compared with much longer durations for LDVs), this approximation may provide a reasonable estimate. The fuel economy estimates assumed for the analysis are illustrated in Figure J-1; as mentioned earlier, only the first 10 years (2016–2026) contributed to the calculations and results described later in this section.

Registered Vehicles

Since one goal of this analysis is to illustrate what the average user would pay in the future, it is necessary to estimate the number of vehicles in the future in order to calculate an average. The projected number of vehicles in 2026 is based on the growth rate in vehicle registrations over the previous 10 years.

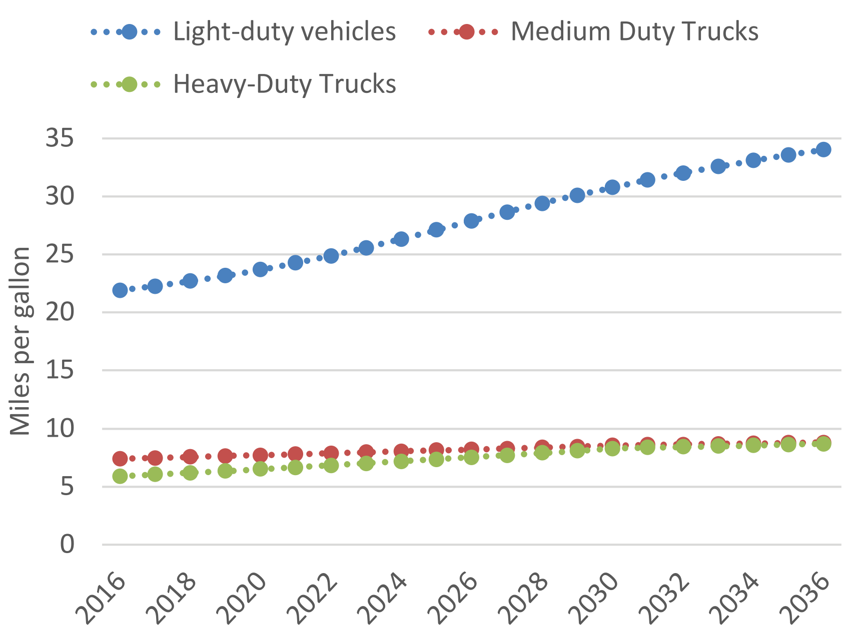

FIGURE J-1 Estimated fuel economy, 2016–2036.

Rate Increases Required

Motor Fuels Rates

As an illustration, this analysis estimated the motor fuels tax rate increases needed for raising an additional $20 billion per year. For the calculation, MPG and VMT were first projected for each class of vehicle for 0.75 percent, 1.5 percent, and 2.0 percent annual VMT growth rates. The estimate of total gallons consumed was then calculated simply by dividing the total VMT by MPG. The number of gallons was multiplied by the fuel tax rates needed to achieve total revenues. Starting with the baseline tax rates, interpolation was used to determine the rate required to raise the desired level of revenue in 2026. In this calculation, the current ratio of gasoline to diesel tax rates was kept constant so that the future tax rates paid by LDVs and trucks would be based on the ratio of the rates paid today. Using conventional approaches to apportioning costs to highway users, the actual rates to be charged would more appropriately be based on an updated cost allocation study, which would estimate the share of cost for highway construction and repair based on the share of design requirements required for, and damage caused by, each vehicle class.

By 2026, and using the mid-range VMT forecast (1.5 percent annual growth), the estimated rates for LDVs to raise an additional $20 billion would have to increase from 18.4 cents per gallon to 30.0 cents per gallon. Diesel rates for trucks would have to increase from 24.4 cents per gallon to 40.0 cents per gallon. These rate increases would be roughly 60 percent over current rates in current dollars. Table J-3 shows the rates and changes to raise $20 billion in new revenue.

Note that this analysis does not adjust for any reductions in projected travel because of the increased cost of travel that would result from the projected rates, although this cost would, presumably, have a small effect on demand.[52] Nor does the analysis account for shifting from gasoline or diesel vehicles to alternatively fueled vehicles that would be induced by higher fuel taxes, though, again, presumably this would have an effect of some magnitude, but it would be offset to the extent that alternatively fueled vehicles were charged fees for highway use able to raise equivalent revenues, per mile traveled, as those charged to users of gasoline or diesel.

Per-Mile Rates

Charging a mileage fee to Interstate users, as described in the MBUF option in Chapter 6 of the report, would enhance both efficiency and equity.

[52] In the case of potential mode shift from truck to rail, the shift would likely be fairly modest. A recent working paper from the Congressional Budget Office estimates that truck tax rates of greater magnitudes than those described herein would cause about 3 percent of truck freight to shift to rail (see Austin 2015).

TABLE J-3 Illustrative Fuel Tax Rate Increase Required to Raise an Additional $20 Billion (current $) in 2026

	Light-Duty Vehicles	Combination Trucks
Current Rate (cents/gal)	18.4	24.4
Required Rate in 2026 (cents/gal)	30.0	40.0
Percentage Change	63	63

If this option were pursued, the amount of funds to be raised would have to be increased to account for the cost of converting the Interstates to an all-electronic tolling system (AET); this cost would be about $55.5 billion, as estimated in Chapter 6. Also for simplicity, we assume that this investment would have a 10-year replacement cycle and that the cost would be amortized over that period; hence adding $5.5 billion per year to the cost of converting the Interstate System to AET. For simplicity, the cost of administration is estimated for the purpose of this analysis to be 10 percent of revenues earned. As a result, instead of needing to raise an additional $20 billion by 2026, the amounts required would be $27.55 billion in current dollars.

If the amount in current motor fuels taxes was converted to a per-mile fee, LDVs would pay about 0.84 cents per mile for use of the Interstates and trucks would pay about 3.28 cents per mile. These rates per mile are well below the average per mile charged for cars (7.7 cents/mi) and paid by trucks (30 cents/mi) on existing toll roads on the Interstate System,[53] but would apply to the entire system.

If vehicles were charged a fee per mile, a key question is what LDVs should pay relative to trucks since loaded truck weights determine the design (and cost) of bridges and truck axle loadings cause most of the damage to pavements. For this analysis, trucks are assumed to pay rates that are four times higher than cars, which is the average that trucks pay more than cars for existing toll roads on Interstates with lengths of 50 miles or more.[54] In order to raise $27.55 billion by 2026, the rates for LDVs would need to rise from 0.84 to 2.72 cents per mile. Rates for combination trucks would need to rise from 3.28 to 10.9 cents per mile. As shown in Table J-4, rates would need to increase by more than fourfold for Interstate users to pay the cost of raising $27.55 billion (in current dollars) by 2026.

[53] Average per-mile equivalents of toll rates for cars and trucks are taken from per-mile equivalents reported for tolls charged on existing toll roads on Interstate highways in the continental United States (FHWA n.d.-a).

[54] The proper way to determine LDV and truck per-mile fees would be through a cost allocation study. This calculation considers tolls on routes of 50 miles or more to avoid the distortions of high truck toll rates on short segments of urban Interstates.

TABLE J-4 Illustrative Interstate User Per-Mile Rate Increase Required to Raise $27.55 Billion (current $) in 2026

	Light-Duty Vehicles	Combination Trucks
Current Rate (cents/mile)	0.84	3.28
Required Rate in 2026 (cents/mile)	2.72	10.9
Change	220%	230%

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASECAP	European Association of Operators of Toll Road Infrastructures
CTS	Centre for Transport Studies
DOT	Department of Transportation
EIA	U.S. Energy Information Administration
FDIC	Federal Deposit Insurance Corporation
FHWA	Federal Highway Administration
GAO	U.S. Government Accountability Office
NZTA	New Zealand Transport Agency
TRB	Transportation Research Board
UDOT	Utah Department of Transportation
U.S. DOT	U.S. Department of Transportation

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