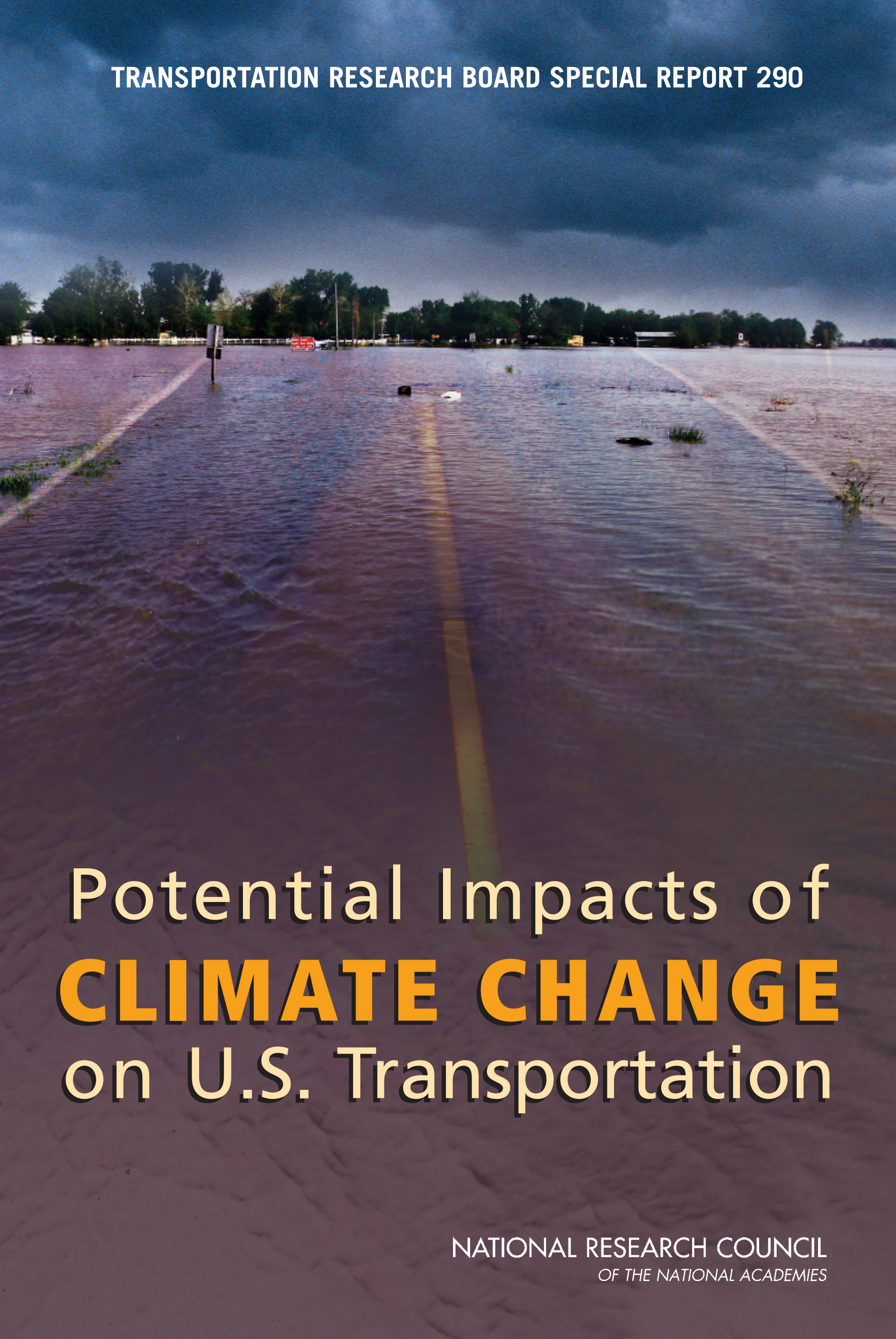
TRANSPORTATION RESEARCH BOARD SPECIAL REPORT 290



Potential Impacts of CLIMATE CHANGE on U.S. Transportation

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Committee on Climate Change and U.S. Transportation
Transportation Research Board
Division on Earth and Life Studies

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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

Leading scientists on the Intergovernmental Panel for Climate Change published their fourth assessment of the state of knowledge about climate change and its impacts in spring 2007. They reached consensus that human activity is responsible for many observed climate changes, particularly the warming temperatures of the last several decades, and concluded that there is a need for far more extensive adaptation than is currently occurring to reduce vulnerability to future climate changes. In September 2007, the National Research Council (NRC) released a report examining the U.S. Climate Change Science Program, which oversees federal research on climate change in the United States. The report noted that understanding of the physical climate system has progressed rapidly but that the use of this knowledge to support decision making, manage risks, and engage stakeholders is inadequate.

The transportation sector is a good case in point. Little consensus exists among transportation professionals that climate change is occurring or warrants action now. Addressing climate change requires an examination of plausible future scenarios, a long-term perspective, the capacity to deal with uncertain and changing information, and responses that may extend beyond jurisdictional boundaries and transportation modal responsibilities. These are significant challenges for transportation professionals. This report is intended to help illuminate the nature of the potential impacts of climate change of greatest relevance for U.S. transportation and to suggest appropriate adaptation strategies and organizational responses.

This study was requested by the Executive Committee of the Transportation Research Board (TRB) and was conducted with the Division on Earth and Life Studies (DELS). It was funded by a broad range of organizations, including TRB, the National Cooperative Highway Research Program, the U.S. Department of Transportation (USDOT), the Transit Cooperative Research Program, the U.S. Environmental Protection Agency, and the U.S. Army Corps of Engineers. TRB and DELS formed a committee of 13 members comprising experts in climate science, meteorology, transportation planning and engineering, transportation operations and maintenance, risk analysis, and economics to conduct the study.[1] The committee was chaired by Henry G. Schwartz, Jr., retired president and chairman of Sverdrup/Jacobs Civil, Inc., and member of the National Academy of Engineering.

To carry out its charge, the committee reviewed the literature in the field, requested numerous briefings, commissioned five papers to explore various aspects of the potential impacts of climate change on U.S. transportation, and held a 1-day conference to explore these issues with a broader audience. The commissioned papers provided the committee with important information on various aspects of the impacts of climate change on transportation. The first paper, by Thomas C. Peterson, Marjorie McGuirk, Andrew H. Horvitz, and Tamara Houston of the National Oceanic and Atmospheric Administration and Michael F. Wehner of the Lawrence Berkeley National Laboratory, helped set the stage by identifying the climate factors of greatest relevance for transportation, summarizing current understanding of projected climate changes for various U.S. regions, and describing potential impacts on transportation. A paper by Michael D. Meyer of the School of Civil and Environmental Engineering at the Georgia Institute of Technology examines the role of transportation design standards in light of potential impacts from climate change. A third paper, by Stephen C. Lockwood of Parsons Brinckerhoff, reviews operational strategies for addressing climate change. A fourth paper, by Lance R. Grenzeback of Cambridge Systematics, Inc., and Andrew Lukmann of the Massachusetts Institute of Technology—a case study of the transportation sector's response to and recovery from Hurricanes Katrina and Rita—examines the vulnerabili-

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[1] George Philander, a member of the National Academy of Sciences, participated as a member of the committee through 2006, when he resigned because of extended foreign travel and new commitments.

ties and strengths of various transportation modes in the event of a shock to the system. A final paper, by James A. Dewar and Martin Wachs of the Rand Corporation,[2] provides a survey of approaches to decision making under uncertainty, drawing on examples from other sectors and suggesting possible new approaches for transportation planning and decision making.

The papers were reviewed by the committee and discussants at a 1-day conference (see next paragraph) and revised by the authors. They are listed in Appendix C. Because of their length and printing costs, the papers are available only in electronic form. The reader is cautioned that the interpretations and conclusions contained in the papers are those of the authors. The key findings endorsed by the committee appear in the body of the report.

The committee recognizes that five papers cannot cover the full range of issues facing the transportation sector as it begins to consider the potential impacts of climate change. Thus, a conference was held midway through the study to examine the papers with a broader audience of climate scientists and academicians and practitioners from all transportation modes and to engage the transportation community in particular in considering the potential impacts of climate change. Each paper was presented and critiqued by a commentator, followed by discussion by the authors and invited participants. The conference concluded with a summary by two rapporteurs—one from the climate science and one from the transportation community. Of the 144 individuals invited to the conference, 51 attended. Their names and affiliations, along with the conference agenda, can be found in Appendix D. The commentary and critiques of conference participants were considered in both finalizing the authored papers and preparing this final report.

The committee also supplemented its expertise with briefings at its meetings from a wide range of experts. In particular, the committee thanks Eric J. Barron, Distinguished Professor of Geosciences and Dean of the College of Earth and Mineral Sciences, Pennsylvania State University (now at the University of Texas at Austin), who provided the committee with an overview of the scientific consensus on climate change, continuing uncertainties, and implications for transportation. The committee also thanks Michael Savonis, Team Leader for Air Quality,

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[2] The authors both work for the Rand Corporation, but the paper was prepared by the authors as individuals.

Federal Highway Administration (FHWA), and Joanne Potter, Senior Associate, Cambridge Systematics, Inc., for their briefing on the Gulf Coast Study sponsored by USDOT and the U.S. Geological Survey—an in-depth look at the potential impacts of climate change in this vulnerable region; Paul Pisano, Team Leader, FHWA, for his presentation on the U.S. Surface Weather Research Program; Ian Buckle, Director of the Center for Civil Engineering Earthquake Research, University of Nevada at Reno, for his briefing on the development of earthquake standards and the relevance of this effort to the revision of transportation design standards to address the potential impacts of climate change; Mark Hinsdale, Assistant Vice President, Capacity Management and Network Planning, CSX Corporation, for his overview of the impacts of Hurricane Katrina on rail infrastructure; and Lourdes Maurice, Chief Scientific and Technical Advisor for Environment, and Mohan Gupta, Operations Research Analyst, Federal Aviation Administration, for their overview of potential impacts of climate change on the aviation system.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that assist the authors and NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee thanks the following individuals for their participation in the review of this report: John J. Boland, Johns Hopkins University (retired), Baltimore, Maryland; William R. Black, Indiana University, Bloomington; Virginia Burkett, U.S. Geological Survey, Many, Louisiana; Isaac M. Held, Princeton University, Princeton, New Jersey; George M. Hornberger, University of Virginia, Charlottesville; Roger E. Kasperson, Clark University, Worcester, Massachusetts; Margaret A. LeMone, National Center for Atmospheric Research, Boulder, Colorado; Ananth Prasad, Florida Department of Transportation, Tallahassee; and Michael J. Scott, Pacific Northwest National Laboratory, Richland, Washington.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the committee's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Susan Hanson, Clark University, Worcester, Massachusetts, and C. Michael Walton, University of Texas at Austin. Appointed by NRC, they were responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Nancy P. Humphrey of TRB, together with Amanda C. Staudt of DELS, managed the study.[3] Ms. Humphrey drafted major portions of the final report under the guidance of the committee and the supervision of Stephen R. Godwin, Director of Studies and Special Programs at TRB, and Chris Elfring, Program Director at DELS. Ms. Staudt drafted Chapter 2, which provides an overview of the current state of knowledge about climate change and its potential impacts; committee members Thomas R. Karl and William J. Gutowski, Jr., made substantial revisions. Committee member George C. Eads wrote Appendix B, which summarizes the contribution of transport-related greenhouse gas emissions to climate change and reviews potential strategies for mitigating these impacts. Suzanne Schneider, Associate Executive Director of TRB, managed the report review process. Special appreciation is expressed to Rona Briere, who edited the report. Jennifer Weeks prepared the final manuscript and the commissioned papers for posting; Norman Solomon provided final editorial guidance; and Juanita Green managed the book design and production under the supervision of Javy Awan, Director of Publications. Amelia Mathis assisted with meeting arrangements and communications with committee members, Laura Toth helped with conference arrangements, and Alisa Decatur provided word processing support for preparation of the final manuscript.

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[3] Ms. Staudt left DELS in February 2007 to join the World Wildlife Federation. Thereafter, Ian Kraucunas and Curtis Marshall of DELS provided assistance with the study.

Contents

Appendices

Summary

The world's leading climate scientists have reached consensus that human activity in the form of greenhouse gas (GHG) emissions is warming the planet in ways that will have profound and unsettling impacts on natural resources, energy use, ecosystems, economic activity, and potentially quality of life. The earth's climate is always in a state of flux, but what is of concern today is the rapid rate of change and the unabated contribution of human activity to its occurrence. Many studies have already examined the potential impacts of climate change on broad sectors of the economy, such as agriculture and forestry, but few have studied the impacts on transportation.

The primary focus of this report is on the consequences of climate change[1] for the infrastructure and operations of U.S. transportation.[2] The report provides transportation professionals with an overview of the scientific consensus on those current and future climate changes of particular relevance to U.S. transportation, including the limitations of present scientific understanding as to their precise timing, magnitude, and geographic location; identifies potential impacts on U.S. transportation and adaptation options; and offers recommendations for both research and actions that can be taken to prepare for climate change. The report also summarizes

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[1] Climate change refers to a statistically significant variation in either the mean state of the climate or its variability over an extended period, typically decades or longer, that can be attributed to either natural causes or human activity. Weather refers to the familiar hour-by-hour, day-by-day changes in temperature, cloudiness, precipitation, and other atmospheric phenomena.

[2] In this report, infrastructure refers to both transportation networks (e.g., road and rail systems) and facilities (e.g., bridges, tunnels, ports). All modes of transportation are covered—highways (including bridges and tunnels), rail (including private rail lines and public transportation), marine and air transportation, and pipelines.

previous work on strategies for reducing transportation-related emissions of carbon dioxide (CO_2)—the primary GHG—that contribute to climate change, a relatively well-researched area (see Appendix B).

Climate change will have significant impacts on transportation, affecting the way U.S. transportation professionals plan, design, construct, operate, and maintain infrastructure. Decisions taken today, particularly those related to the redesign and retrofitting of existing or the location and design of new transportation infrastructure, will affect how well the system adapts to climate change far into the future. Focusing on the problem now should help avoid costly future investments and disruptions to operations. The primary objective of this report is to provide guidance for transportation decision makers on how best to proceed.

CLIMATE CHANGES OF GREATEST RELEVANCE FOR U.S. TRANSPORTATION

Climate change is not just a problem for the future. Recent global climate changes, such as warming temperatures and rising sea levels, likely reflect the effects of GHG emissions into the atmosphere over the past century. Even if drastic measures were taken today to stabilize or eliminate GHG emissions, the effects of climate change would continue to be experienced, and U.S. transportation professionals would have to adapt to their consequences.

On the basis of current knowledge, climate scientists have identified five climate changes of particular importance to transportation and estimated the probability of their occurrence during the 21st century (detailed in Box S-1):

- Increases in very hot days and heat waves,
- Increases in Arctic temperatures,
- Rising sea levels,
- Increases in intense precipitation events, and
- Increases in hurricane intensity.

Climate scientists have the greatest confidence in projected changes in mean temperature and other climate factors at the global or continental scale; confidence in these projections diminishes as the geographic scale is

Box S-1

Climate Change Impacts of Greatest Relevance for U.S. Transportation

Increases in very hot days and heat waves. It is highly likely (greater than 90 percent probability of occurrence) that heat extremes and heat waves will continue to become more intense, longer lasting, and more frequent in most regions during the 21st century. In 2007, for example, the probability of having five summer days at or above 43.3°C (110°F) in Dallas was about 2 percent. In 25 years, this probability increases to 5 percent; in 50 years, to 25 percent; and by 2099, to 90 percent.

Increases in Arctic temperatures. Arctic warming is virtually certain (greater than 99 percent probability of occurrence), as temperature increases are expected to be greatest over land and at most high northern latitudes. As much as 90 percent of the upper layer of permafrost could thaw under more pessimistic emission scenarios. The greatest temperature increases in North America are projected to occur in the winter in northern parts of Alaska and Canada as a result of feedback effects of shortened periods of snow cover. By the end of the 21st century, projected warming could range from as much as 10.0°C (18.0°F) in the winter to as little as 2.0°C (3.6°F) in the summer in the northernmost areas. On an annual mean temperature basis for the rest of North America, projected warming ranges from 3.0°C to 5.0°C (5.4°F to 9.0°F), with smaller values near the coasts.

Rising sea levels. It is virtually certain (greater than 99 percent probability of occurrence) that sea levels will continue to rise in the 21st century as a result of thermal expansion and loss of mass from ice sheets. The projected global range in sea level rise is from 0.18 m (7.1 in.) to 0.59 m (23.2 in.) by 2099, but the rise will not be geographically uniform. The Atlantic and Gulf Coasts should experience a rise near the global mean, the West Coast a slightly lower rise, and the Arctic Coast a rise of only 0.1 m (3.9 in.). These estimates do not include subsidence in the Gulf and uplift along the New England Coast. Nor do the global projections include the full effects of increased melting of the Greenland and Antarctic ice masses because current understanding of these effects is too limited to permit projection of an upper bound on sea level rise.

Increases in intense precipitation events. It is highly likely (greater than 90 percent probability of occurrence) that intense precipitation events will continue to become more frequent in widespread areas of the United States.

(continued)

Box S-1 (continued)

Climate Change Impacts of Greatest Relevance for U.S. Transportation

Increases in hurricane intensity. Increased tropical storm intensities, with larger peak wind speeds and more intense precipitation, are projected as likely (greater than 66 percent probability of occurrence). No robust projections concerning the annual global number of tropical storms have yet emerged from modeling studies, but more detailed analyses focused on the Atlantic Ocean suggest no significant increases in the annual number of Atlantic tropical storms.

Note: The primary sources for these data are the 2007 Intergovernmental Panel for Climate Change *Summary for Policymakers on the Physical Science Basis* (Contribution of Working Group I to the Fourth Assessment Report); the Peterson et al. 2006 paper commissioned for this study (see Appendix C); numerous other sources that can be found in Chapter 2 (see Table 2-1 and the text discussing each of these impacts); and the committee's own assessments about the certainty of some impacts, based on the literature.

reduced. Nevertheless, climate scientists are now able to project climate changes for large subcontinental regions, such as the eastern United States—a scale better suited to transportation infrastructure, which is regional and local. Projections of future climate are often shown as gradual changes, such as the rise in global temperatures projected over this century. However, these changes are unlikely to be experienced in such a smooth manner because those induced by human activity will be amplified in some years by naturally fluctuating conditions, reflected in potentially sudden and dramatic changes at the regional or local level. For example, many climate scientists caution that warming temperatures may trigger weather extremes and surprises, such as more rapid melting of the Arctic sea ice or more rapid rises in sea levels than are projected by current models.

> ***Finding:*** *The past several decades of historical regional climate patterns commonly used by transportation planners to guide their operations and investments may no longer be a reliable guide for future plans. In particular, future climate will include new classes (in terms of magnitude and frequency) of weather and climate*

> *extremes,*[3] *such as record rainfall and record heat waves, not experienced in modern times as human-induced changes are superimposed on the climate's natural variability.*

POTENTIAL IMPACTS ON TRANSPORTATION

Transportation professionals are keenly aware of the effects of weather on system performance. Transportation infrastructure was designed for typical weather patterns, reflecting local climate and incorporating assumptions about a reasonable range of temperatures and precipitation levels.

> ***Finding:*** *Climate change will affect transportation primarily through increases in several types of weather and climate extremes, such as very hot days; intense precipitation events; intense hurricanes; drought; and rising sea levels, coupled with storm surges and land subsidence. The impacts will vary by mode of transportation and region of the country, but they will be widespread and costly in both human and economic terms and will require significant changes in the planning, design, construction, operation, and maintenance of transportation systems.*

The infrastructure will be affected most by those climate changes that cause environmental conditions to extend outside the range for which the system was designed (see Table S-1 for illustrative impacts of key climate changes).

> ***Finding:*** *Potentially, the greatest impact of climate change for North America's transportation systems will be flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence.*

Fully 53 percent of the U.S. population now lives in counties with coastal regions, many among the most densely populated in the nation. As retirement magnets and tourist destinations with rapidly growing economies, coastal communities will continue to experience development pressures,

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[3] The exact threshold for what is classified as an extreme varies from one analysis to another, but an extreme event would normally be as rare as or rarer than the top or bottom 10 percent of all occurrences. For the purposes of this report, all tornadoes and hurricanes are considered extreme.

TABLE S-1 **Potential Climate Changes and Illustrative Impacts on Transportation**

Potential Climate Change	Examples of Impacts on Operations	Examples of Impacts on Infrastructure
Increases in very hot days and heat waves	Impact on lift-off load limits at high-altitude or hot-weather airports with insufficient runway lengths, resulting in flight cancellations or limits on payload (i.e., weight restrictions), or both Limits on periods of construction activity due to health and safety concerns	Thermal expansion on bridge expansion joints and paved surfaces Concerns regarding pavement integrity (e.g., softening), traffic-related rutting, migration of liquid asphalt Rail-track deformities
Increases in Arctic temperatures	Longer ocean transport season and more ice-free ports in northern regions Possible availability of a northern sea route or a northwest passage	Thawing of permafrost, causing subsidence of roads, rail beds, bridge supports (cave-in), pipelines, and runway foundations Shorter season for ice roads
Rising sea levels, combined with storm surges	More frequent interruptions to coastal and low-lying roadway travel and rail service due to storm surges More severe storm surges, requiring evacuation or changes in development patterns	Inundation of roads, rail lines, and airport runways in coastal areas More frequent or severe flooding of underground tunnels and low-lying infrastructure

	Potential for closure or restrictions at several of the top 50 airports that lie in coastal zones, affecting service to the highest-density populations in the United States	Erosion of road base and bridge supports Reduced clearance under bridges Changes in harbor and port facilities to accommodate higher tides and storm surges
Increases in intense precipitation events	Increases in weather-related delays and traffic disruptions Increased flooding of evacuation routes Increases in airline delays due to convective weather	Increases in flooding of roadways, rail lines, subterranean tunnels, and runways Increases in road washout, damages to rail-bed support structures, and landslides and mudslides that damage roadways and tracks Increases in scouring of pipeline roadbeds and damage to pipelines
More frequent strong hurricanes (Category 4–5)	More frequent interruptions in air service More frequent and potentially more extensive emergency evacuations More debris on roads and rail lines, interrupting travel and shipping	Greater probability of infrastructure failures Increased threat to stability of bridge decks Impacts on harbor infrastructure from wave damage and storm surges

increasing the exposure of people and businesses to harm from extreme weather. The Atlantic and Gulf Coasts are particularly vulnerable because they have already experienced high levels of erosion, land subsidence, and loss of wetlands. Seven of the 10 largest U.S. ports (by tons of traffic), as well as significant oil and gas production facilities, are located on the Gulf Coast, an area whose vulnerability to disruption and damage was amply demonstrated during the 2005 tropical storm season. Sea level rise and coastal flooding also pose risks for the East Coast, as well as the Pacific Northwest and parts of the California Coast.

The vulnerability of transportation infrastructure to climate change will extend beyond coastal areas. For example, watersheds supplying water to the St. Lawrence Seaway and the Great Lakes, as well as the Upper Midwest river system, are likely to experience drier conditions, resulting in lower water levels and reduced capacity to ship agricultural and other bulk commodities, although a longer shipping season could offset some of the adverse economic effects. Thawing permafrost in Alaska is already creating settlement and land subsidence problems for roads, rail lines, runways, and pipelines. Higher temperature extremes (mainly heat waves) in some U.S. regions could lead to more frequent buckling of pavements and misalignment of rail lines. More severe weather events with intense precipitation could increase the severity of extensive flooding events, such as the storms that plagued the Midwest during the 1993 flooding of the Mississippi and Missouri River system, the Chicago area in 1996, and the Houston region during Tropical Storm Allison in 2001. Flooding of a waterway system can knock out barge operations on the river itself, rail operations on rights-of-way adjacent to the river, and even highway approaches to bridges crossing flooded rivers.

Not all climate change impacts will be negative. For example, the marine transportation sector could benefit from more open seas in the Arctic, creating new and shorter shipping routes and reducing transport time and costs. In cold regions, expected temperature rises, particularly decreases in very cold days and later onset of seasonal freezes and earlier onset of seasonal thaws, could mean reduced costs of snow and ice control for departments of transportation and safer travel conditions for passenger vehicles and freight.

Recommendation 1: Federal, state, and local governments, in collaboration with owners and operators of infrastructure,

> **such as ports and airports and private railroad and pipeline companies, should inventory critical transportation infrastructure in light of climate change projections to determine whether, when, and where projected climate changes in their regions might be consequential.**

These inventories would need to be updated periodically as new scientific knowledge about climate change becomes available. This would be a relatively low-cost activity because a large portion of the necessary information and tools [e.g., geographic information systems (GIS)] is likely to be available. The inventorying process itself should also help identify with greater precision the data needed from climate scientists on transportation-relevant climate changes.

DECISION FRAMEWORK

Transportation decision makers have an opportunity now to prepare for projected climate changes.

> ***Finding:*** *Public authorities and officials at various governmental levels and executives of private companies are continually making short- and long-term investment decisions that have implications for how the transportation system will respond to climate change in the near and long terms.*
>
> **Recommendation 2: State and local governments and private infrastructure providers should incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans.**

Taking measures now to evaluate and protect the most vulnerable infrastructure should pay off by diminishing near-term maintenance expenditures and reducing the risk of catastrophic failure, with its toll on human life and economic activity (see Box S-2, which presents a six-step approach for determining appropriate investment priorities). Such measures might include strengthening or elevating some coastal roads, rail lines, and bridges, particularly those that serve as evacuation routes, or upgrading parallel routes where they are available. In the longer term, relocation

Box S-2

Decision Framework for Transportation Professionals to Use in Addressing Impacts of Climate Change on U.S. Transportation Infrastructure

1. Assess how climate changes are likely to affect various regions of the country and modes of transportation.
2. Inventory transportation infrastructure essential to maintaining network performance in light of climate change projections to determine whether, when, and where the impacts could be consequential.
3. Analyze adaptation options to assess the trade-offs between making the infrastructure more robust and the costs involved. Consider monitoring as an option.
4. Determine investment priorities, taking into consideration the criticality of infrastructure components as well as opportunities for multiple benefits (e.g., congestion relief, removal of evacuation route bottlenecks).
5. Develop and implement a program of adaptation strategies for the near and long terms.
6. Periodically assess the effectiveness of adaptation strategies and repeat Steps 1 through 5.

of rights-of-way farther inland or installation of costly storm barrier systems to protect selected areas (e.g., parts of New York City or Miami) might be considered. Prudent choices today could avoid some of these costs.

> ***Finding:*** *The significant costs of redesigning and retrofitting transportation infrastructure to adapt to potential impacts of climate change suggest the need for more strategic, risk-based approaches to investment decisions.*

Traditionally, transportation decision makers have not taken full advantage of quantitative, risk-based approaches that incorporate uncertainty and probabilistic assessments in making investment and design decisions. Nor will past trends provide a reliable guide for future plans and designs as they relate to climate.

> **Recommendation 3: Transportation planners and engineers should use more probabilistic investment analyses and design**

> **approaches that incorporate techniques for trading off the costs of making the infrastructure more robust against the economic costs of failure. At a more general level, these techniques could also be used to communicate these trade-offs to policy makers who make investment decisions and authorize funding.**

One model is the California Seismic Retrofit Program, which uses a risk-based approach for analyzing vulnerability to earthquakes and the criticality of highway bridges to determine priorities for retrofitting and replacement. Adapting such techniques to address climate change will require continuing education of current planners and engineers and training of future professionals. It will also require educating policy makers to gain their support and may well necessitate new eligibility criteria in funding programs and new funding sources so the investments identified by the application of these techniques can be made.

DATA AND DECISION SUPPORT TOOLS

Transportation decision makers note that one of the most difficult aspects of addressing climate change is obtaining the relevant information in the form needed for planning and design purposes. Specifically, as noted earlier, climate change is understood with greatest confidence as a global phenomenon, while transportation planners need local and regional climate projections. They also need a better understanding of how projected climate changes, such as changes in temperature and precipitation, will affect the environment (e.g., soil moisture, runoff) in which the infrastructure is situated, which will vary from region to region.

> ***Finding:*** *Transportation professionals often lack sufficiently detailed information about expected climate changes and their timing to take appropriate action.*

Simply put, transportation professionals, climate scientists, hydrologists, and others have not communicated well.

> **Recommendation 4: The National Oceanic and Atmospheric Administration, the U.S. Department of Transportation**

> **(USDOT), the U.S. Geological Survey, and other relevant agencies should work together to institute a process for better communication among transportation professionals, climate scientists, and other relevant scientific disciplines, and establish a clearinghouse for transportation-relevant climate change information.**

All professions should benefit from the collaboration. Transportation professionals would be encouraged to define with greater precision the climate data needed to make better transportation decisions, such as temperature and precipitation thresholds at finer-grained geographic scales or climate conditions that would create unacceptable performance outcomes. Climate scientists would be challenged to elaborate on the possibilities and limitations of projecting the impacts of climate change at the levels of geographic specificity that are most useful for transportation planners. And hydrologists and others would be challenged to consider how the environment would influence these effects and their impacts on transportation infrastructure.

> ***Finding:*** *Better decision support tools are also needed to assist transportation decision makers.*

> **Recommendation 5: Ongoing and planned research at federal and state agencies and universities that provide climate data and decision support tools should include the needs of transportation decision makers.**

For example, the research program of the USDOT Center for Climate Change and Environmental Forecasting could be charged with expanding its existing research program in this area and provided the necessary funding. Needed tools include highly accurate digital elevation maps in coastal areas for forecasting the effects of flooding and storm surge heights; GIS that can be used to map the locations of critical infrastructure, overlaid with information on climate change effects (e.g., sea level rise, permafrost melt); greater use of scenarios that include climate change in the development of long-range regional transportation plans to pinpoint likely vulnerabilities and ways to address them; and better network models for examining the systemwide effects of the loss of critical transportation infrastructure links.

ADAPTATION OPTIONS

Numerous studies have examined ways of mitigating the transportation sector's contribution to global warming from GHG emissions. Far less attention has been paid to the potential impacts of climate change on U.S. transportation and how transportation professionals can best adapt to climate changes that are already occurring and will continue to occur into the foreseeable future, even if drastic mitigation measures were taken today.

Operational Responses

Climate extremes and abrupt changes, such as storms and precipitation of increased intensity, will require near-term operational responses from transportation providers. U.S. transportation providers already address the impacts of weather on transportation system operations in a diverse range of climatic conditions. For example, snow and ice control accounts for about 40 percent of annual highway operating budgets in the northern states. Likewise, hurricane planning has become a major focus of transportation operations in the Gulf Coast states, where transportation providers are forging close relationships with emergency responders to handle severe weather events.

As climate changes induce new extremes, operational responses are likely to become more routine and proactive than today's approach of treating severe weather on an ad hoc, emergency basis. For example, if hurricanes increase in intensity, as is likely to be the case, establishment of evacuation routes and use of contraflow operations may become as commonplace as the current use of snow emergency routes in the Northeast and Midwest. More accurate and timely weather prediction and communication of storm warnings in real time to those potentially in harm's way will become more important.

> ***Finding:*** *Projected increases in extreme weather and climate underscore the importance of emergency response plans in vulnerable locations and require that transportation providers work more closely with weather forecasters and emergency planners and assume a greater role in evacuation planning and emergency response.*
>
> **Recommendation 6: Transportation agencies and service providers should build on the experience in those locations**

where transportation is well integrated into emergency response and evacuation plans.

Monitoring and Use of Technology

Monitoring infrastructure conditions, particularly the impacts of extreme climate changes, offers an alternative to preventive retrofitting or reconstruction of some facilities. In Alaska, for example, the Alyeska Pipeline Company constantly monitors the right-of-way of the Trans-Alaska Pipeline System to spot land subsidence problems, particularly along the 800 miles of pipeline elevated on vertical supports. Alaskan engineers also closely monitor bridge supports that are experiencing damage from earlier winter runoff and increased stream flow. In the future, sensors and other smart technologies could be embedded in the infrastructure to monitor climate conditions and impacts.

Finding: *Greater use of technology would enable infrastructure providers to monitor climate changes and receive advance warning of potential failures due to water levels and currents, wave action, winds, and temperatures exceeding what the infrastructure was designed to withstand.*

Recommendation 7: Federal and academic research programs should encourage the development and implementation of monitoring technologies that could provide advance warning of pending failures due to the effects of weather and climate extremes on major transportation facilities.

Sharing of Best Practices

As the climate changes, many U.S. locations will experience new climate-induced weather patterns.

Finding: *The geographic extent of the United States—from Alaska to Florida and from Maine to Hawaii—and its diversity of weather and climate conditions can provide a laboratory for identifying best practices and sharing information as the climate changes.*

Recommendation 8: The American Association of State Highway and Transportation Officials (AASHTO), the Federal

> **Highway Administration, the Association of American Railroads, the American Public Transportation Association, the American Association of Port Authorities, the Airport Operators Council, associations for oil and gas pipelines, and other relevant transportation professional and research organizations should develop a mechanism to encourage sharing of best practices for addressing the potential impacts of climate change.**

This effort should build on existing technology transfer mechanisms, such as AASHTO's technology-sharing program. Technology should be defined broadly to include probabilistic decision-making tools, as well as monitoring technologies, new materials, and operating and maintenance strategies.

Design Changes

Environmental factors are integral to the design of transportation infrastructure. Conditions such as temperature, freeze–thaw cycles, and duration and intensity of precipitation determine subsurface and foundation design, choice of materials, and drainage capacity. Engineers, however, have given little thought to whether current design standards are sufficient to accommodate climate change. For example, will drainage capacity be adequate for expected increases in intense precipitation events? Many infrastructure components are currently designed for the 100-year storm—an event of such severity that it occurs, on average, once in 100 years. But projections indicate that what is today's 100-year precipitation event is likely to occur every 50 or perhaps even every 20 years by the end of the current century. What new materials might be needed when very hot temperatures and heat waves become more frequent? Are infrastructure components sufficiently strong to withstand the forces of larger and more frequent storm surges and more powerful wave action, the effects of which were vividly demonstrated when Hurricane Katrina simply lifted bridge decks off their supporting structures?

> ***Finding:*** *Reevaluating, developing, and regularly updating design standards for transportation infrastructure to address the impacts of climate change will require a broad-based research and testing program and a substantial implementation effort.*

Developing consensus standards is a time-consuming process. Changes in design practices tend to be incremental, and building to higher standards must be weighed against the cost involved. Thus there is a need for a selective, risk-based approach to making changes in standards that focuses first on long-lived facilities, such as bridges and large culverts. A good model is the congressionally mandated National Earthquake Hazard Reduction Program, begun in 1977, which established a research effort and a coordination mechanism designed to reduce the risks to life and property from earthquakes through standards that would afford different levels of protection for different levels of risk. If a similar program is to be launched to address climate change in a timely manner, it should be initiated soon.

> **Recommendation 9: USDOT should take a leadership role, along with those professional organizations in the forefront of civil engineering practice across all modes, to initiate immediately a federally funded, multiagency research program for ongoing reevaluation of existing and development of new design standards as progress is made in understanding future climate conditions and the options available for addressing them. A research plan and cost proposal should be developed for submission to Congress for authorization and funding of this program.**

The initial focus should be on essential links in transportation networks, particularly those vulnerable to climate change in coastal or other low-lying areas in riverside locations.

> **Recommendation 10: In the short term, state and federally funded transportation infrastructure rehabilitation projects in highly vulnerable locations should be rebuilt to higher standards, and greater attention should be paid to the provision of redundant power and communications systems to ensure rapid restoration of transportation services in the event of failure.**

The development of appropriate design standards to accommodate climate change is only one of several possible adaptation strategies.

> ***Finding:*** *Federal agencies have not focused generally on adaptation in addressing climate change.*

> **Recommendation 11: USDOT should take the lead in developing an interagency working group focused on adaptation.**

This initiative would not necessarily require new funding beyond that recommended above. Better collaboration among agencies could help focus attention on adaptation issues and shape existing research programs.

Transportation Planning and Land Use Controls

One of the most effective strategies for reducing the risks of climate change is to avoid placing people and infrastructure in vulnerable locations. Transportation planners currently consider expected land use patterns when forecasting future travel demand and infrastructure needs. However, they rarely question whether such development is desirable, much less what effects climate change might have on the provision and development of infrastructure in vulnerable locations. In part, this situation stems from governance arrangements. States, regional authorities, and the private sector are responsible for large-scale transportation investment decisions, but local governments and a few states control land use decisions through comprehensive plans, zoning ordinances, permitting, and building codes.

> ***Finding:*** *Transportation planners are not currently required to consider climate change impacts and their effects on infrastructure investments, particularly in vulnerable locations.*

> **Recommendation 12: Federal planning regulations should require that climate change be included as a factor in the development of public-sector long-range transportation plans; eliminate any perception that such plans should be limited to 20 to 30 years; and require collaboration in plan development with agencies responsible for land use, environmental protection, and natural resource management to foster more integrated transportation–land use decision making.**

Current surface transportation legislation encourages such collaboration. During reauthorization, requiring transportation planners to both consider climate change and collaborate with land use planners in the preparation of public-sector long-range plans could go a long way toward putting these issues on the table. At the same time, any strategy employing land use controls to address climate change would need to build consensus among key decision makers in transportation and land use, probably at the regional level—a challenging proposition.

> ***Finding:*** *Locally controlled land use planning, which is typical throughout the country, has too limited a perspective to account for the broadly shared risks of climate change.*

Insurance

Private insurers may be able to accomplish what government cannot in terms of land use control. Some major insurers, for example, are refusing to write new or renew existing homeowners' policies in areas already vulnerable to hurricanes and other severe storms, which could intensify in a warming climate. Florida, Texas, Louisiana, Mississippi, Hawaii, New York City, and Long Island are among the areas affected thus far. Some states have stepped up to become insurers of last resort for coastal homes and businesses, but the high costs of providing coverage are unlikely to be sustainable. Moreover, the provision of insurance in hazard-prone areas that is not actuarially based is bad public policy.

The federal government is the insurer of last resort for homeowners in specially designated flood hazard areas. The National Flood Insurance Program of the Federal Emergency Management Agency (FEMA) provides homeowners with below-cost insurance. In return, the local community must adopt and enforce floodplain management measures, including building code ordinances for new construction and rebuilding after a disaster, to reduce flood damage. Critics contend that in practice, the program has resulted in more development than would otherwise have occurred in these areas. Moreover, the accuracy of flood insurance rate maps (FIRMs) used to determine program eligibility is woefully inadequate, despite a mapping modernization program. Flood hazard area boundaries are keyed to the 100-year storm, and base elevation data are inadequate.

> ***Finding:*** *The National Flood Insurance Program and the FIRMs used to determine program eligibility do not take climate change into account.*

> **Recommendation 13: FEMA should reevaluate the risk reduction effectiveness of the National Flood Insurance Program and the FIRMs, particularly in view of projected increases in**

> **intense precipitation and storms. At a minimum, updated flood zone maps that account for sea level rise (incorporating land subsidence) should be a priority in coastal areas.**

New Organizational Arrangements

The impacts of climate change do not follow modal, corporate, or jurisdictional boundaries, yet decision making in the transportation sector is structured around these boundaries. Transportation planning is conducted primarily at the regional level, often through a bottom-up process that starts with local jurisdictions. Railroads, trucking, and waterborne commerce are largely private enterprises with varying levels of federal participation. Thus, existing institutional arrangements are not well suited to addressing climate change. Some models of cross-jurisdictional cooperation exist, such as regional authorities for specific facilities (e.g., the Alameda Corridor) and multistate emergency response agreements. In addition, there are models of state-mandated regional authorities, as is the case for regional air quality improvement authorities. Organizational arrangements suited to addressing the impacts of climate change may require state or federal action.

> ***Finding:*** *Current institutional arrangements for transportation planning and operations were not organized to address climate change and may not be adequate for the purpose.*
>
> **Recommendation 14: Incentives incorporated in federal and state legislation should be considered as a means of addressing and mitigating the impacts of climate change through regional and multistate efforts.**

For example, states could use updated FIRMs or their own state maps to identify geographic areas vulnerable to climate change and craft policies for restricting transportation investments and limiting insurance in these locations.

CONCLUDING THOUGHTS

The committee finds compelling scientific evidence that climate change is occurring and that it will trigger new, extreme weather events and could possibly lead to surprises, such as more rapid than expected rises in sea levels or temperature changes. Every mode of transportation will be affected as climate change poses new and often unfamiliar challenges to infrastructure providers. The committee urges that the transportation community start now to confront these challenges.

A strong federal role is needed to implement many of the committee's recommendations that require broad-based action or regulation, such as creation of a clearinghouse for information on transportation and climate change, the research program to reevaluate existing and develop new design standards for addressing climate change, creation of an interagency working group on adaptation, changes in federal regulations regarding long-range planning guidelines and infrastructure rehabilitation requirements, and reevaluation of the National Flood Insurance Program.

Many of the committee's recommendations, however, need not await federal action. Local governments and private infrastructure providers can begin to identify critical infrastructure that is particularly vulnerable to climate change. Professional organizations can begin to amass examples of best practice, and planners and climate scientists at local universities and research institutes can begin to collaborate on the development of regional scenarios of likely transportation-related climate changes and the data needed to analyze their impacts. The most important step, however, is for transportation professionals to acknowledge that the time has come to confront the challenges posed by climate change and to incorporate the most current scientific knowledge into the planning, design, construction, operation, and maintenance of transportation systems.

1

Introduction

Climate scientists are projecting changes in the global climate with potentially profound impacts on agriculture and forest productivity, ecosystems, water resources, and energy, as well as related socioeconomic effects.[1] Increases in annual globally averaged mean temperatures, in the number of warm days and nights over mid- and high-latitude land areas, and in temperature and precipitation extremes all are projected to occur with a high degree of confidence[2] during the 21st century. These changes will bring about the retreat of sea ice and the thawing of glaciers and ice caps, particularly at high northern latitudes; rising sea levels; and greater flooding and higher storm surges along vulnerable coastal and riverine areas. The finer the geographic resolution and the longer the temporal projections, the greater are the uncertainties surrounding estimates of future climate change. The respective roles of human and natural causes in these changes have now been well established (IPCC 2007b).

Numerous studies have examined the link between climate change and the transportation sector. These studies have been conducted primarily

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[1] Climate change refers to a statistically significant variation in either the mean state of the climate or its variability over an extended period, typically decades or longer, that can be attributed to either natural causes or human activity (IPCC 2007a). This definition is drawn from the Intergovernmental Panel on Climate Change (IPCC), which was jointly established by the World Meteorological Organization and the United Nations Environment Programme in 1988 to assess the available scientific and socioeconomic information on climate change and its impacts and on options for mitigating those impacts and developing adaptive responses.

[2] Climate scientists express uncertainty in a variety of ways. To encourage greater uniformity in communicating uncertainty, lead authors of the IPCC Fourth Assessment Report were provided guidance on how to treat issues of uncertainty and statistical confidence in a consistent manner (IPCC 2005). The term "high degree of confidence" means consistency across model projections and/or consistency with theory and/or changes in the mean. See Chapter 2 for a more detailed discussion of uncertainty.

from the perspective of transportation's contribution to global warming through the burning of fossil fuels, which releases carbon dioxide (CO_2) and other greenhouse gases (GHGs) into the atmosphere.[3] CO_2 from combustion of fossil fuels is the largest source of U.S. GHG emissions. In 2005, the most recent year for which data are available, the transportation sector accounted for 33 percent of U.S. CO_2 emissions from fossil fuel combustion,[4] exceeded only by electricity generation by the electric power industry at 41 percent (USEPA 2007, Table 3-7).[5] CO_2 emissions from U.S. transportation activities are expected to increase over the next several decades, primarily as a result of growth in road travel, fueled by population and economic growth (World Business Council for Sustainable Development 2004). However, these emissions are likely to be regulated. In a landmark decision in April 2007 (*Massachusetts et al., Petitioners, v. Environmental Protection Agency et al.*), the U.S. Supreme Court ruled that the U.S. Environmental Protection Agency has the authority under the Clean Air Act to regulate GHG emissions and that CO_2 can be construed as an air pollutant under the statute.

Far less attention has been paid to the consequences of potential climate changes for U.S. transportation infrastructure and operations.[6, 7] For example, projected rising sea levels, flooding, and storm surges could swamp marine terminal facilities, airport runways near coastlines, subway and railroad tunnel entrances, and roads and bridges in low-lying coastal areas.

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[3] CO_2 and other GHGs allow sunlight to enter and prevent heat from leaving the earth's atmosphere—the so-called greenhouse effect, loosely analogous to the operation of a greenhouse window. Higher concentrations of CO_2 and other GHGs than occur naturally trap excess heat in the atmosphere and warm the earth's surface (Staudt et al. 2005).

[4] Emissions from combustion of both aviation and marine international bunker fuels (i.e., fuel loaded on transport vehicles in the United States but consumed in international operations) are excluded from this total. See Appendix B for a more detailed discussion of the transportation sector's contribution in general, and the U.S. contribution in particular, to worldwide GHG emissions, particularly emissions of CO_2 from fuel combustion.

[5] The total is larger if emissions from the extraction, production, and distribution of transport fuels and from the manufacture, distribution, and disposal of transportation vehicles are summed to produce a total life-cycle emissions estimate (see the discussion in Appendix B).

[6] In this report, infrastructure refers to both transportation networks (e.g., road and rail systems) and facilities (e.g., bridges, tunnels, ports).

[7] In fact, a recent assessment of the U.S. Climate Change Science Program (CCSP) found that the scientific community is not well structured to develop information that would enable adaptive response for any sector in the United States (NRC 2007). The CCSP integrates federal research on climate and global change, as sponsored by 13 federal agencies.

Across the northern portions of the contiguous United States, warmer temperatures and reduced lake ice will likely lead to increased evaporation from bodies of water and their surrounding watersheds, potentially lowering lake and river levels and reducing vessel-carrying capacity. Shipping across the Great Lakes and the Upper Midwest river system would thereby be impaired, although a longer shipping season would offset some of the adverse economic effects. Thawing permafrost in Alaska is already creating settlement and land subsidence problems for roads, rail lines, runways, and pipelines. Greater temperature extremes (mainly heat waves) in some U.S. regions could lead to buckling of pavements and misalignment of rail lines. More intense precipitation could increase the severity of flooding events, such as the storms that plagued the Midwest during the flooding of the Mississippi River in 1993 and the Chicago area in 1996. More intense tropical storms, like Hurricanes Katrina and Rita, which ravaged the Gulf Coast in 2005, are likely to become more frequent. However, no significant increases in the annual number of Atlantic tropical storms are projected.

The vulnerability[8] of the transportation sector to these impacts has not been thoroughly studied, nor has it been widely considered by transportation planners and decision makers in planning, designing, constructing, retrofitting, and operating the transportation infrastructure. Many transportation professionals are unaware of the problems climate change could create. Others are hesitant to take action in view of the uncertain outcomes and long time frames involved and the lack of clear guidelines and standards for addressing the effects of climate change and related hazards.

STUDY CHARGE, SCOPE, AND AUDIENCE

The Executive Committee of the Transportation Research Board (TRB) requested and provided funding for this study, which was undertaken jointly with the Division on Earth and Life Studies of the National

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[8] One in-depth assessment of impacts in the Gulf Coast region, entitled *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study,* was ongoing during the course of this study. It became available for public comment only after the committee had completed its deliberations. The public review version of the Gulf Coast study can be accessed at www.climatescience.gov/Library/sap/sap4-7/public-review-draft/default.htm.

Academies. The expert committee formed to conduct the study was charged[9] to

- Provide federal, state, and local transportation officials in the United States with an overview of the scientific consensus regarding climate change, including uncertainty about its nature and extent;
- Summarize previous work on strategies for reducing transportation's impact on climate change;
- Summarize possible impacts on transportation, such as those due to rising sea levels, higher mean temperatures with less extreme low temperatures and more heat extremes, and more frequent intense precipitation events;
- Analyze options for adapting to these impacts, including the possible need to alter assumptions about infrastructure design and operations, the ability to incorporate uncertainty into long-range decision making, and the capability of institutions to plan and act on mitigation and adaptation strategies at the state and regional levels;
- Identify critical areas for research; and
- Suggest policies and actions for preparing for the potential impacts of climate change.

The committee's charge can be viewed more broadly as a risk management problem with hazards to address (potential impacts of climate change) and vulnerable[10] assets to protect (transportation infrastructure). Seen in this framework, the objective is to minimize risk by reducing the hazards (i.e., identify mitigation measures to reduce the potential effects of climate change) and protecting the assets (i.e., identify adaptation mea-

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[9] A more detailed statement of task is included as Appendix A.

[10] In this report, the term "vulnerability" is defined as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC 2007a, 21). The committee notes that there is a large literature on vulnerability as it relates to many hazards and cites Turner et al. (2003) as an example of a broad vulnerability framework and its application to several different types of hazards and affected communities in case studies.

sures[11] to strengthen the infrastructure and increase its resilience to changing climate conditions through more stringent design standards and construction codes and retrofitting or relocation of at-risk facilities).[12]

The primary focus of this report is on adaptation strategies rather than on strategies to mitigate transportation-related GHG emissions. The topic of adaptation, particularly as it relates to transportation, has not received the attention or research effort devoted to the issue of mitigation. Investigating both topics fully was beyond the resources available for this study. In fact, at the time of this writing, TRB had initiated a new study focused entirely on mitigation.[13] Nevertheless, in response to its charge and drawing heavily on existing studies, committee member George Eads, with the consensus of the full committee, summarized current and projected contributions of the transportation sector to GHG emissions and examined numerous technological and nontechnological mitigation strategies (see Appendix B). The analysis did not attempt to pick winners and losers by comparing the costs and benefits of alternative mitigation approaches. Indeed, the data for doing so were not available. That level of analysis would require a separate study or even a series of studies.

The committee was mindful of the potential interaction between mitigation and adaptation strategies as shown in Figure 1-1. For example, if the fuel consumption and CO_2 emissions and concentrations of transportation vehicles could be substantially reduced by the introduction of new technologies, this would lessen the human-caused contribution to climate change and its impacts on transportation infrastructure. Reductions in travel demand or shifts to less GHG-emitting travel modes (e.g., public transit for personal travel and rail for freight travel) would operate in a similar fashion. The summary of Appendix B notes, however, that a common

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[11] Adaptation strategies refer to human attempts to protect or adapt systems so as to reduce the risks and moderate the potential harm from and exploit the beneficial opportunities of the impacts of climate change. Mitigation strategies refer to human intervention to reduce the sources of GHGs that contribute to climate change.

[12] Until researchers can quantify both the severity of expected outcomes and their probabilities, however, a full risk assessment is not possible.

[13] The study on potential energy savings and GHG reductions will review policies and strategies to affect behavior and improve fuel economy for passenger and freight vehicles across all modes; develop scenarios to illustrate potential savings over a 25- to 50-year time horizon for the United States; and analyze the safety, economic, transportation finance, and environmental consequences of energy-saving measures.

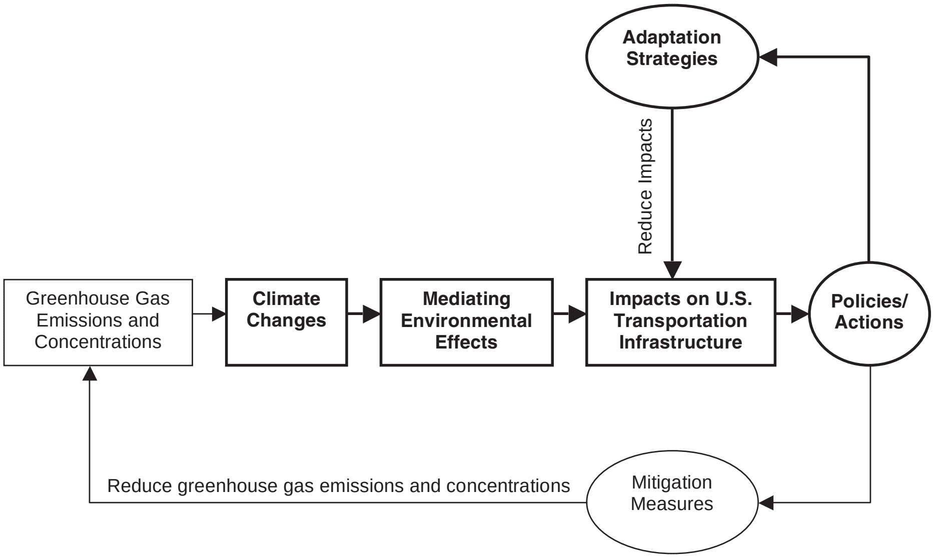

FIGURE 1-1 **Role of mitigation measures and adaptation strategies in addressing climate change impacts on U.S. transportation infrastructure.** (Bolded areas denote the primary focus of this study.)

characteristic of these mitigation measures is the considerable time they would take to be fully effective[14] and the fact that they would affect only future GHG emissions and concentration levels. Complementary adaptation strategies are thus essential if the transportation sector is to address the consequences of GHG emissions and concentration levels that have already occurred.

The report begins with an overview of the current state of knowledge about climate change and its potential impacts, with a particular focus on North America, to set the stage for assessing the consequences for the transportation sector and identifying prudent adaptation strategies. The objective of this review is not to advance the state of climate science but

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[14] The appendix notes that the time required to develop, commercialize, and disseminate new vehicle technologies is probably shorter than the time required to alter the fundamental drivers of demand for personal and freight transport—growth in real income, population growth, urbanization, and changes in urban form. Nevertheless, both new technology and shifts in demand are needed if future levels of transportation-related GHG emissions—a major source of total GHG emissions—are to be significantly reduced.

to inform transportation professionals about climate change—including uncertainty as to its precise timing and geographic locations—so they can begin to consider appropriate responses.

The report encompasses all modes of transportation—highways (including bridges and tunnels), rail (including private rail lines and public transportation), marine and air transportation, and pipelines. Its primary focus is on the direct impacts of climate change on transportation infrastructure and system operating performance, although indirect impacts are noted (e.g., potential shifts in the location of economic activities and use of transportation modes, pollution impacts). These indirect impacts are highly uncertain because they depend on assumptions about population and economic growth, the rate of technological innovation, and policy decisions (e.g., government regulations and controls on coastal land use and development, private-sector decisions about business operations and logistics).

The geographic scope of the study is confined to the United States but extends beyond the contiguous 48 states to include Alaska, Hawaii, and the U.S. territories.[15] The range of weather and climate conditions[16] embraced by this area is broad—from the permafrost conditions of Alaska to the tropical conditions of Puerto Rico and Hawaii. Thus, the United States can expect a wide range of climate changes and their impacts. International studies were reviewed for techniques and approaches that might be appropriate to the United States. However, the committee found few studies that address the impact of climate change on transportation and adaptation strategies.

The audience for this report is the transportation community broadly defined. The overall goal of the report is to demonstrate to decision makers responsible for transportation infrastructure—both public and private—why they should plan for climate change. At the same time, an attempt is made to moderate expectations about the level of precision with which the report can provide guidance on specific impacts of climate change and their time frames.

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[15] Information on climate change effects and impacts, however, is not always available for smaller geographic areas.

[16] Climate change refers to a statistically significant variation in either the mean state of the climate or its variability over an extended period, typically decades or longer, that can be attributed to either natural causes or human activity. Weather refers to the familiar hour-by-hour, day-by-day changes in temperature, cloudiness, precipitation, and other atmospheric phenomena.

WHY CLIMATE CHANGE MATTERS

When asked to consider climate change, transportation professionals frequently protest that dealing with a problem whose time horizon is decades and centuries and whose effects are uncertain is impractical. Moreover, they maintain, resources are insufficient to address day-to-day maintenance problems, much less to make investments on the basis of changes that may or may not occur years or even generations into the future.

So why should transportation professionals take note of climate change? First, it is not just a problem for the future. Recent changes, such as global warming and resulting sea level rises, reflect the effects of GHG emissions that were released into the atmosphere over the past century. What appears to be new is the greater certainty of scientists that human activity is already warming the climate and that the rate of change is likely to be greater than at any time in modern history (IPCC 2007b).

Second, climate change will not necessarily occur gradually. Climate scientists expect that higher temperatures will be amplified by normal variability in climate, leading to new extremes far outside current experience [e.g., the heat wave in Europe in 2003 (Stott et al. 2004) and the near record heat of 2006 in the United States (Hoerling et al. 2007)]. Higher temperatures are also likely to trigger surprises, such as more rapid than expected melting of Arctic sea ice and rising sea levels.

Third, although transportation professionals typically plan 20 to 30 years into the future, many decisions taken today, particularly about the location of infrastructure, help shape development patterns and markets that endure far beyond these planning horizons. Similarly, decisions about land use, zoning, and development often create demand for long-lived transportation infrastructure investments. Thus, it is important for transportation decision makers to consider potential impacts of climate change now in making these investment choices because those impacts will affect how well the infrastructure adapts to climate change.

Fourth, professionals in many fields—among them finance, building (where protecting against earthquakes, wildfires, or wind risk is a concern), nuclear power, and water resources (in the design of dams and canals)—are continually making decisions in the face of uncertain information about risks and outcomes. In fact, the highway and bridge engineering community, through the auspices of the American Association of State Highway and Transportation Officials, has developed design guidelines and standards for earthquake resistance on the basis of probabilistic seismic hazard assessments that take many uncertainties into account. Similarly, addressing climate change requires more quantitative assessments, such as the development of probabilistic climate change scenarios at the level of geographic and modal specificity needed by transportation planners and engineers, which can be incorporated into planning forecasts and engineering design guidelines and standards.

Finally, transportation professionals already consider weather- and climate-related factors in designing and operating the transportation infrastructure. For example, many transportation networks and facilities are designed with adequate drainage and pumping capacity to handle a 100-year storm.[17] Materials and maintenance cycles are geared to assumptions about temperature and precipitation levels. Evacuation plans and routes have been identified in hurricane- and other storm-prone locations on the basis of current elevations and assumptions about storm surges and wave action. But what if the 100-year storm were to become the 50- or 30-year storm, or design thresholds were frequently to be exceeded, or evacuation routes themselves were to become vulnerable (see Box 1-1)? Such changes could necessitate different design criteria, asset management policies, maintenance cycles, and operating strategies. Recent severe weather events—such as the Mississippi River floods of 1993, Category 3 or greater hurricanes (e.g., Ivan, Katrina, Rita), the California wildfires of 2003—provide ample opportunities for transportation professionals to observe the vulnerabilities of the infrastructure to shocks to the system that could become more commonplace in the future. They also illustrate the dilemma facing transportation decision makers of whether to rebuild, rebuild differently, or relocate critical transportation infrastructure.

STUDY APPROACH AND KEY ISSUES

A wide range of climate changes could affect transportation infrastructure and result in changes in the way U.S. transportation professionals plan, design, operate, and maintain the infrastructure. The committee adapted a figure from a workshop conducted by the U.S. Department of

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[17] A 100-year storm is defined as the amount of rainfall during a specified length of time that has a 1 percent chance of being equaled or exceeded in any given year or, put another way, has a recurrence interval of 100 years.

Box 1-1

What If?

- What if design lives for infrastructure and return periods were to be exceeded routinely? Many facilities are built to withstand a 100-year storm. The design of other facilities, such as bridges, assumes a 50-year storm and does not take into account the effect of wave action, vividly illustrated by Hurricane Katrina (Meyer 2006). What if the 50-year storm, or even the 100-year storm, were to be exceeded routinely, reducing projected recurrence periods to much below one in 50 or one in 100 years?

- What if multiple severe weather events were to occur? Each year, Florida and the Gulf Coast brace for hurricanes, and California prepares for wildfires or heavy rains. Emergency personnel are generally able to handle these events, and transportation managers find alternative routes to keep freight moving, largely because the events occur sequentially and at relatively infrequent intervals. But consider the impact of a Category 4 or 5 hurricane directed at Houston and its critical petrochemical infrastructure at the same time that torrential rains and mudslides prevent access to the Port of Los Angeles. How would emergency responders and the economy fare in the face of multiple and simultaneous intense storms that climate change could bring with greater frequency?

- What if critical evacuation routes were themselves to become submerged by rising seas and storm surge? Population increases in coastal areas are projected to more than double in the next 20 years. Many seaside communities count on coastal highways for evacuation in a major storm. Some of these highways also act as flood barriers. What if the current accelerating rate of sea level rise were to continue into the foreseeable future? Highways in low-lying areas that provide a vital lifeline could themselves become compromised by encroaching seas and storm surge. Some communities could be cut off in a severe storm or would be forced to evacuate well in advance of the storm's known trajectory to avoid that risk. In the longer term, it may be possible to relocate some coastal highways farther inland and still provide a means of egress for vulnerable communities.

Transportation (USDOT 2003) on the potential impacts of climate change on transportation (Potter and Savonis 2003) to provide a conceptual framework for this study (Figure 1-2). The first task is to identify potential climate change effects, focusing on those of greatest relevance for transportation (see Column 1). This task also includes indicating what is known from climate scientists about the certainty of these effects, particularly at the regional and local levels, and the time frame over which they are likely to unfold.

The second task (see Column 2) involves describing the impacts of the effects of climate change on transportation. These impacts can be considered in several different ways—by type of climate change effect (e.g., sea level rise, temperature extremes), by transportation mode, by geographic area, and by type of impact. With regard to the latter, impacts on transportation can be direct (i.e., affecting the physical infrastructure as well as

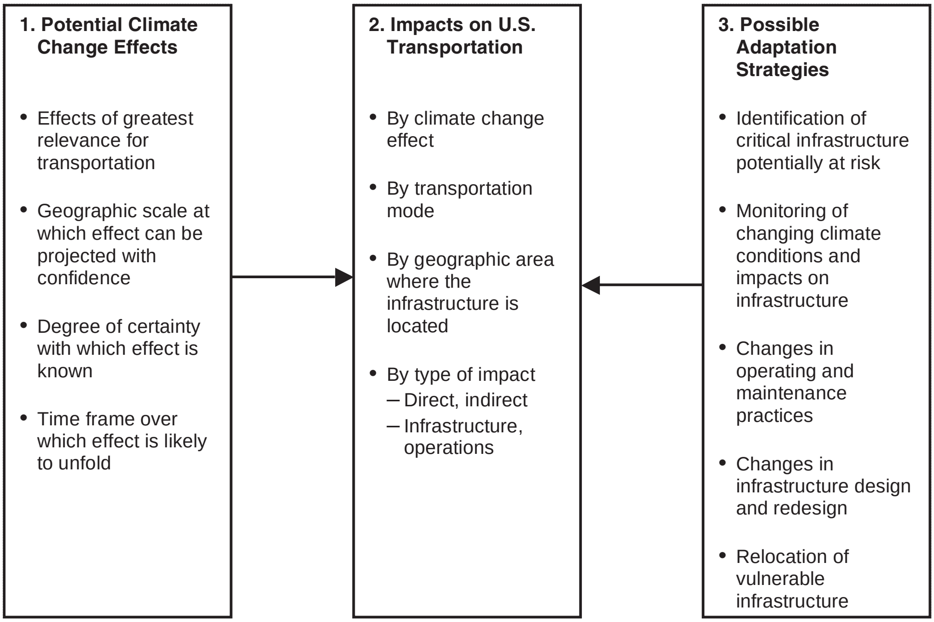

FIGURE 1-2 **Potential impacts of climate change on transportation infrastructure.** [Note in Column 2 that the impacts of climate change on U.S. transportation infrastructure will be influenced by the environment in which the infrastructure is located (e.g., soil moisture, stream flow), which will vary from region to region.] (*Source*: Adapted from Potter and Savonis 2003, 29.)

the operating performance of the system) or indirect (e.g., affecting the location of economic activities or levels of pollution). Finally, these impacts will be influenced by changes in the environment in which the infrastructure is situated. For example, changes in temperature and precipitation will affect soil moisture and runoff, which in turn will affect peak stream flows, sediment delivery to coasts, and the sustainability of the landforms upon which the infrastructure is built, with considerable regional variability. The tasks listed in Columns 1 and 2 require good communication among climate scientists, transportation professionals, and other relevant scientific disciplines.

The final task (see Column 3) requires developing possible adaptation strategies. A range of approaches is suggested—from the identification of at-risk critical infrastructure, to the monitoring of conditions (both climate and infrastructure), to changes in operating and maintenance practices, to changes in infrastructure design and redesign, to relocation of vulnerable infrastructure. The strategies listed in this column require action primarily by transportation decision makers—planners, designers, engineers, and operating and maintenance personnel.

Figure 1-2 links together potential climate change effects, impacts on U.S. transportation infrastructure, and possible adaptation strategies, but it does not fully address several key points. First, issues of scale affect the certainty with which the effects of climate change on transportation infrastructure can be examined at present. Climate change projections are most accurate at the global level, but transportation infrastructure is largely local and regional. Nevertheless, the ability to predict climate change at the local and regional levels is improving. Furthermore, the effects of climate change are not point specific; their impacts may differ even within a region, depending on location. For example, sea level rise will affect coastal regions, but the seriousness of the impact will depend on the elevation, the amount of land subsidence, and the extent of protection (e.g., levees) provided and the redundancy of vulnerable infrastructure in the affected areas.

The network character of transportation infrastructure adds another layer of complexity. Adverse impacts of climate change on transportation facilities in one region, for example, may shift activity to another location or route, either temporarily, as was the case for freight movement in the wake of Hurricane Katrina, or in the longer term (e.g., shifts in port activity resulting from new shipping routes opening as a result of warming and deepening seas), with net effects that may be positive or negative.

Differences in time frames are another complicating factor. Some climate changes will unfold over decades and centuries, ostensibly allowing time for transportation decision makers to plan and respond. Others are likely to increase the sensitivity of the climate system and could bring surprises and abrupt changes that would make planning difficult.[18] The lifetime of transportation infrastructure can be as little as 10 to 20 years (e.g., some pavement surfaces), allowing engineers to adapt to some climate changes as they unfold. Many other transportation networks and facilities are longer-lived. Major bridges and pipelines, for example, have lifetimes of 50 to 100 years, while the right-of-way of major transportation networks (e.g., rail lines, roads) is easily that long-lived. Thus, many of the investment decisions made by transportation professionals today will have a significant effect on how well the infrastructure adapts to climate change.

Finally, like so many other problems, climate change will not be experienced in isolation. It will manifest itself in the context of other demographic, social, and economic trends, often aggravating existing conditions. For example, many coastal areas are likely to experience increased development pressures as a result of population growth, greater affluence, and tourist demands. Many of these areas are already vulnerable to erosion and storm damage. As sea levels rise with global warming, coastal storms with higher tides and storm surges are likely to create the conditions for more severe coastal flooding and erosion, placing more people in harm's way and increasing the difficulty of evacuating in an emergency.

ORGANIZATION OF THE REPORT

The remainder of this report addresses the committee's charge. Chapter 2 reviews the current state of knowledge about climate change, including projected changes over the next century, and those factors of particular relevance to U.S. transportation. Chapter 3 is focused on the potential impacts of climate changes on transportation infrastructure. The chapter begins with an overview of the vulnerability of the infrastructure to these changes; it then examines the likely impacts of the most critical climate changes by transportation mode, reviews the handful of studies that have examined the impacts of climate change on transportation, and draws a

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[18] Evidence exists for abrupt climate changes that can occur within a decade. The Dust Bowl drought of the 1930s is a good example (NRC 2002).

series of findings. Chapter 4 describes how the transportation sector is organized and explains why climate change poses a difficult challenge to decision makers. It concludes with some suggestions for a more strategic, risk-based approach to investment decisions. Chapter 5 considers adaptation strategies—both engineering and operational measures, as well as changes in transportation planning and land use controls, development of new technologies, improved data and analysis tools, and organizational changes. In the sixth and final chapter, the committee offers its recommendations for policies and actions to address the impacts of climate change on transportation and for needed research.

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Abbreviations

IPCC	Intergovernmental Panel on Climate Change
NRC	National Research Council
USDOT	U.S. Department of Transportation
USEPA	U.S. Environmental Protection Agency

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2

Understanding Climate Change

This chapter begins with an overview of current understanding of the role greenhouse gases (GHGs) play in the atmosphere and evidence for how they are already influencing the earth's climate in both general and specific ways. The discussion includes a review of the climate change projections of global climate models and some of the evidence that has led recent national and international scientific assessments—including those of the Intergovernmental Panel on Climate Change (IPCC) (2007), the National Research Council (2001), and the Climate Change Science Program (CCSP) Synthesis and Assessment Report 1.1 (Karl et al. 2006)—to link the rise in temperature, particularly since the 1970s, to increases in GHGs. Next is a discussion of the projected climate changes for North America most relevant for U.S. transportation. For each climate variable, past projections and key uncertainties are also discussed. The chapter ends with a series of findings.

OVERVIEW OF GLOBAL CLIMATE CHANGE

The Greenhouse Effect and Atmospheric Composition

The natural "greenhouse" effect is real and is an essential component of the planet's climatic processes. A small proportion (roughly 2 percent) of the atmosphere is, and long has been, composed of GHGs (water vapor, carbon dioxide, ozone, and methane). These gases effectively prevent part of the heat radiated by the earth's surface from otherwise escaping to space. The response of the global system to this trapped heat is a climate that is warmer than it would be without the presence of these gases; in their absence, the earth's temperature would be too low to support life as we know it. Among the GHGs, water vapor is by far the most dominant, but other gases augment its effect through greater trapping of heat in certain portions of the electromagnetic (light) spectrum.

In addition to the natural greenhouse effect outlined above, a change is under way in the greenhouse radiation balance. Some GHGs are proliferating in the atmosphere because of human activities and increasingly trapping more heat. Direct atmospheric measurements made over the past 50 years have documented steady growth in the atmospheric abundance of carbon dioxide (CO_2). In addition to these direct, real-time measurements, ice cores have revealed the atmospheric CO_2 concentrations of the distant past. Measurements using air bubbles trapped within layers of accumulating snow show that atmospheric CO_2 has increased by nearly 35 percent over the Industrial Era (since 1750), compared with its relatively constant abundance over at least the preceding 10,000 years (see Figure 2-1). The predominant causes of this increase in CO_2 are the combustion of fossil fuels and deforestation. Further, the abundance of methane has doubled over the Industrial Era, although its increase has slowed during the past decade for reasons not clearly understood. Other heat-trapping gases are also increasing as a result of human activities. Scientists are unable to state with certainty the rate at which these GHGs will continue to increase because of uncertainties in future emissions, as well as in how these emissions will be taken up by the atmosphere, land, and oceans. They are certain, however, that once in the atmosphere, these gases have a relatively long residence time, on the order of a century (IPCC 2001). This means they become well mixed across the globe.

There is no doubt that the composition of the atmosphere is affected by human activities. Today GHGs are the largest human influence on atmospheric composition. The increase in GHG concentrations in the atmosphere implies a positive radiative forcing (i.e., a tendency to warm the climate system).

Increases in heat-trapping GHGs are projected to be amplified by feedback effects, such as changes in water vapor, snow cover, and sea ice. As atmospheric concentrations of CO_2 and other GHGs increase, the resulting rise in surface temperature leads to less sea ice and snow cover, causing the planet to absorb more of the sun's energy rather than reflecting it back to space, thereby raising temperatures even further. Present evidence also suggests that as GHGs lead to rising temperatures, evaporation

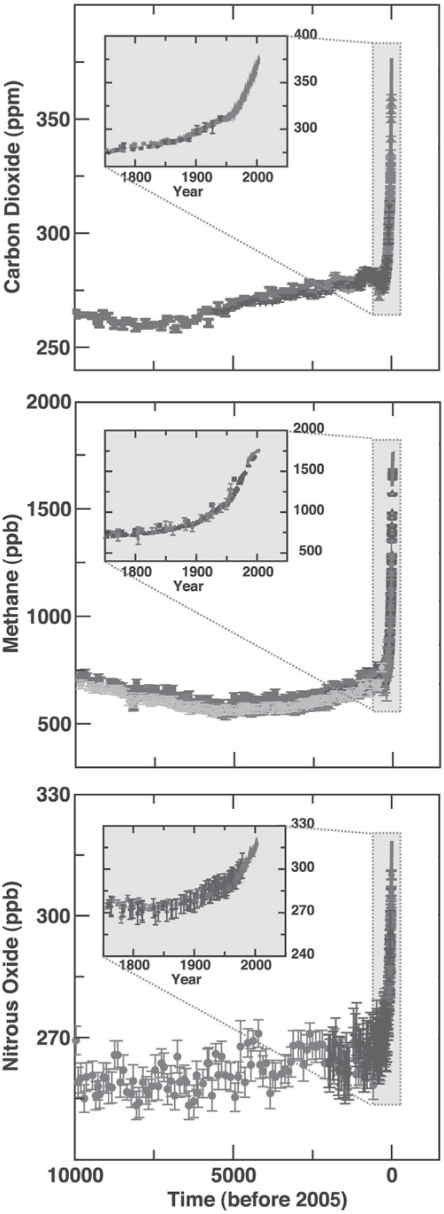

FIGURE 2-1 **Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide over the past 10,000 years (large panels) and since 1750 (inset panels).** Measurements are from a combination of ice cores (going back 10,000 years) and atmospheric samples in the 20th century. (*Source:* IPCC 2007, Figure SPM-1, p. 15. Reprinted with permission of the IPCC Secretariat, Geneva, Switzerland.)

increases, leading to more atmospheric water vapor (Soden et al. 2005; Trenberth et al. 2005). Additional water vapor, the dominant GHG, acts as a very important feedback to increase temperature further. The most uncertain feedback is related to clouds, specifically changes in cloud frequency, location, and height. The range of uncertainty spans from a significant positive feedback to no feedback, or even a slightly negative feedback. Present understanding suggests that these feedback effects account for at least half of the climate's warming (IPCC 2001; Karl and Trenberth 2003). The exact magnitude of these effects remains a significant source of uncertainty in understanding the impact of increasing GHGs. Increases in evaporation and water vapor affect global climate in other ways besides causing rising temperatures, such as increasing rainfall and snowfall rates and accelerating drying during droughts.

Particles suspended in the atmosphere (aerosols) resulting from human activities can also affect climate. Aerosols vary considerably by region. Some aerosol types (e.g., sulfate) act in a way opposite to the GHGs by reflecting more solar radiation back to space than the heat they absorb, and thereby causing a negative radiative forcing or cooling of the climate system. Other aerosols (e.g., soot) act in the same way as GHGs and warm the climate. In contrast to the long-lived nature of CO_2, aerosols are short-lived and removed from the lower atmosphere within a few days. Therefore, human-generated aerosols exert a long-term forcing on climate only because their emissions continue each day of the year. The effects of aerosols on climate can be manifested directly by their ability to reflect and trap heat, but also indirectly by changes in the lifetime of clouds and in the clouds' reflectivity to sunshine. The magnitude of the negative forcing of the indirect effects of aerosols is highly uncertain, but it may be larger than that of their direct effects (IPCC 2001).

Emissions of GHGs and aerosols continue to alter the atmosphere by influencing the planet's natural energy flows (see Box 2-1), which can cause changes in temperature and precipitation extremes, reductions in snow cover and sea ice, changes in storm tracks, and increased intensity of hurricanes (IPCC 2007). There are also natural factors that exert a forcing effect on climate [e.g., changes in the sun's energy output and short-lived (a few years) aerosols in the stratosphere following episodic and explosive volcanic eruptions]. If all the possible influences of natural and human climate forcings over the past several decades are considered, increases in GHGs have had a larger influence on the planet's radiation flow than all the

Box 2-1

What Warms and Cools the Earth?

The sun is the earth's main energy source. Its output appears nearly constant, but small changes during an extended period of time can lead to climate changes. In addition, slow changes in the earth's orbit affect how the sun's energy is distributed across the earth, creating another variable that must be considered.

Greenhouse gases warm the earth:

Water vapor (H_2O), supplied from oceans and the natural biosphere, accounts for two-thirds of the total greenhouse effect but acts primarily as a feedback. In contrast to other greenhouse gases, the amount of water vapor in the atmosphere generally cannot be controlled by humans. Water vapor introduced directly into the atmosphere from agricultural or other activities does not remain there very long and is overwhelmed by natural sources; thus it has little warming effect.

Carbon dioxide (CO_2) has natural and human sources. CO_2 levels are increasing as a result of the burning of fossil fuels.

Methane (CH_4) has both human and natural sources and has risen significantly since preindustrial times as the result of an increase in several human activities, including raising of livestock; growing of rice; use of landfills; and extraction, handling, and transport of natural gas.

Ozone (O_3) has natural sources, especially in the stratosphere, where changes caused by ozone-depleting chemicals have been important; ozone also is produced in the troposphere (the lower part of the atmosphere) when hydrocarbons and nitrogen oxide pollutants react.

Nitrous oxide (N_2O) has been increasing from agricultural and industrial sources.

Halocarbons continue to be used as substitutes for chlorofluorocarbons (CFCs) as refrigerant fluids, and CFCs from pre–Montreal Protocol usage as refrigerants and as aerosol-package propellants remain in the atmosphere.

Scientists have a high level of understanding of the human contributions to climate forcing by carbon dioxide, methane, nitrous oxide, and CFCs and a medium level of understanding of the human contributions to climate forcing by ozone (Forster et al. 2007).

(continued)

Some aerosols (airborne particles and droplets) warm the earth:

Black carbon particles, or "soot," produced when fossil fuels or vegetation is burned, generally have a warming effect by absorbing solar radiation.

Some aerosols cool the earth:

Sulfate (SO_4) aerosols from burning of fossil fuels reflect sunlight back to space.
Volcanic eruptions emit gaseous sulfur dioxide (SO_2), which, once in the atmosphere, forms SO_4 aerosols and ash. Both reflect sunlight back to space.

Scientists currently have a low level of understanding of the human contributions to climate forcing by aerosols (Forster et al. 2007).

Changes in land cover, ice extent, and cloud cover can warm or cool the earth:

Deforestation produces land areas that reflect more sunlight back to space; replacement of tundra by coniferous trees that create dark patches in the snow cover may increase absorption of sunlight.
Sea ice reflects sunlight back to space; reduction in the extent of sea ice allows more sunlight to be absorbed into the dark ocean, causing warming.
Clouds reflect sunlight back to space but can also act like a greenhouse gas by absorbing heat leaving the earth's surface; the net effect depends on how the cloud cover changes.

Source: Adapted from Staudt et al. 2006, p. 7.

other forcings, one that continues to grow disproportionately larger (IPCC 2007; Karl and Trenberth 2003).

Human activities also have a large-scale impact on the earth's land surface. Changes in land use due to urbanization and agricultural practices, although not global, are often most pronounced where people live, work, and grow food and are part of the human impact on climate. Land use changes affect, for example, how much of the sun's energy is absorbed or reflected and how much precipitation evaporates back into the atmosphere. Large-scale deforestation and desertification in Amazonia and the Sahel, respectively, are two instances in which evidence suggests the likelihood of a human influence on regional climate (Andreae et al. 2004; Chagnon and Bras 2005). In general, city climates differ from those in surrounding rural green areas, causing an "urban heat island" due to greater heat retention of urban surfaces, such as concrete and asphalt, as well as the waste generated from anthropogenic activities[1] (Bornstein and Lin 2000; Changnon et al. 1981; Jones et al. 1990; Karl et al. 1988; Landsberg 1983; Peterson 2003).

What Is a Climate Model and Why Is It Useful?

Many of the scientific laws governing climate change and the processes involved can be quantified and linked by mathematical equations. Figure 2-2 shows schematically the kinds of processes that can be included in climate models. Among them are many earth system components, such as atmospheric chemistry, ocean circulation, sea ice, land surface hydrology, biogeochemistry,[2] and atmospheric circulation. The physics of many, though not all, of the processes governing climate change are well understood and may be described by mathematical equations. Linking these equations creates mathematical models of climate that may be run on computers or supercomputers. Coupled climate models can include mathematical equations describing physical, chemical, and biogeochemical processes and are used because the climate system is composed of different interacting components.

Coupled climate models are the preferred approach to climate modeling, but they cannot at present include all details of the climate system. One reason is that not all details of the climate system are understood, even though the major governing processes are known well enough to allow models to reproduce observed features, including trends, of global climate. Another reason is the prohibitive complexity and run-time requirements of models that might incorporate all known information about the climate system. Decisions on how to build any given climate model include trade-offs among the complexity of the model and the number of earth system components included, the model's horizontal and spatial resolution, and the number of

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[1] The global effects of these urban heat islands have been analyzed extensively and assessed to ensure that they do not bias measurements of global temperature.

[2] Biogeochemistry refers to the biological chemistry of the earth system, such as the uptake of atmospheric carbon by land and ocean vegetation.

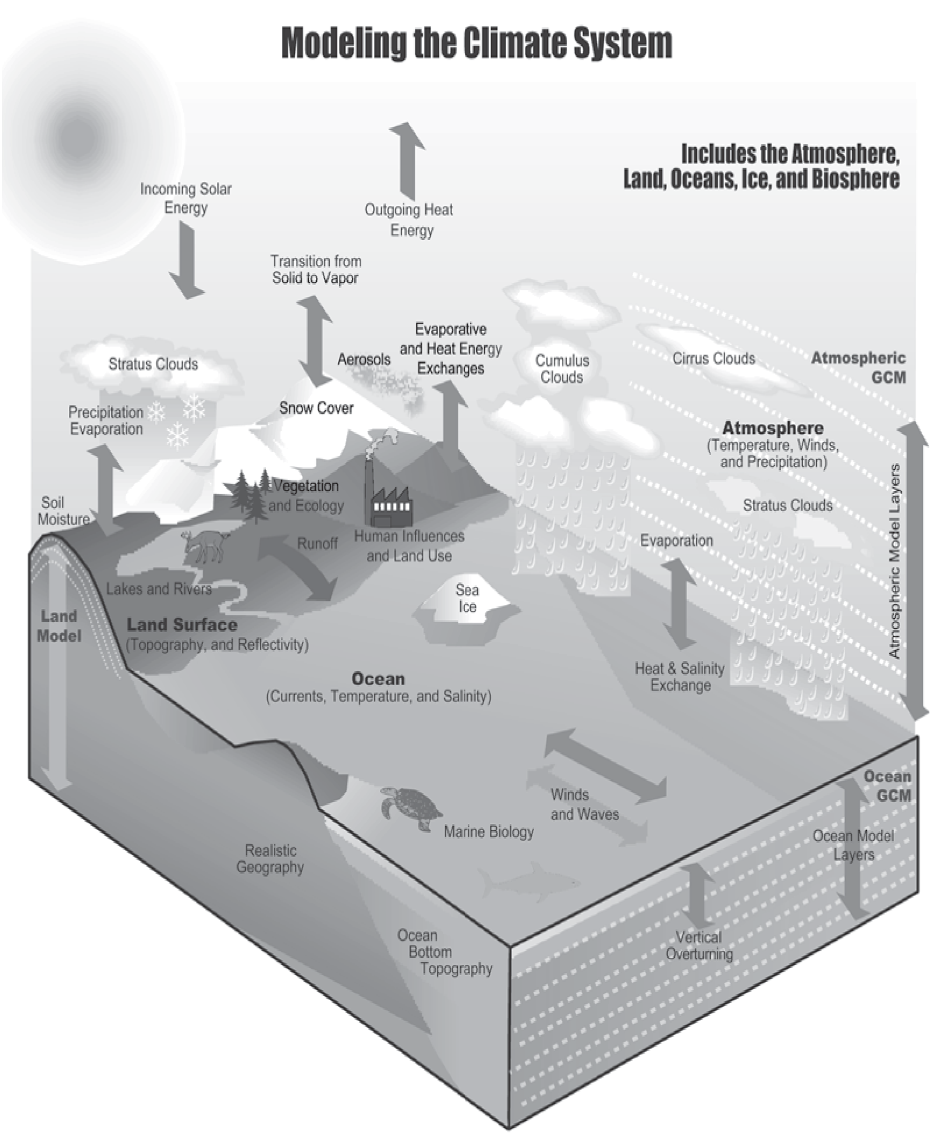

FIGURE 2-2 **Components of the climate system and their interactions, including the human component.** All these components must be modeled as a coupled system that includes the oceans, atmosphere, land, cryosphere, and biosphere. GCM = General Circulation Model. (*Source:* Karl and Trenberth 2003, Figure 3. Reprinted from *Science,* Vol. 302, No. 5651, with permission.)

years of simulations the model can produce per day of computer time. Consequently, there is a hierarchy of models of varying complexity, often based on the degree to which approximations are required for each model or component processes omitted.

Approximations in climate models represent aspects of the models that require parameter choices and "tuning." As a simple example, imagine representing a single cumulus cloud in a global climate model. The cloud may encompass only a few hundred meters in vertical and horizontal space—a much finer resolution than can be run on today's coupled atmosphere and ocean climate models. As a result, if such clouds are to be incorporated into the climate model, some approximations must be made regarding the clouds' statistical properties within, say, an area 100 or 1,000 times larger than the cloud itself. This is referred to as model parameterization, and the process of selecting the most appropriate parameters to best simulate observed conditions is called model tuning. Similar methods are also required in today's state-of-the-science weather forecasting models.

An important difference between weather forecasting models and climate models is that the former are initialized with a specific set of observations representing today's weather to predict the weather precisely *x* days or hours into the future. By contrast, the initial conditions of climate models are much less important. Also, climate models are not intended to predict specific future weather events. Rather, they are used to simulate many years of "weather" into the future with the intent of understanding the change in the collection of weather events at some point in the future compared with some point in the past (often the climate of the past 30 years or so). Scientists are thus interested in properties of climate, such as average rainfall and temperature and the degree of fluctuation about that average. This comparison enables scientists to study the output of climate model simulations to understand the effect of various modifications of those aspects of the climate system that might cause the climate to change. A key challenge in climate modeling is to isolate and identify cause and effect. Doing so requires knowledge about the changes and variations in the external forcings controlling climate and a comprehensive understanding of climate feedbacks (such as a change in the earth's reflectivity because of a change in the amount of sea ice or clouds) and natural climate variability. A related key challenge in climate modeling is the representation of sub-grid-scale processes, such as in some storms, and land-terrain effects.

Model simulations of climate over specified periods can be verified and validated against the observational record. Likewise, model parameterization schemes for particular processes of interest can be tested by comparison with observations and with higher-resolution, smaller-scale models. Models that describe climate variability and change well can be used as a tool to increase understanding of the climate system. Once evaluated and validated, climate models can then be used for predictive purposes. Given specific forcing scenarios, the models can provide viable projections of future climate. In fact, climate models have become the primary means of projecting climate change, although ultimately, future projections are likely to be determined through a variety of means, including the observed rate of global climate change.

How Do We Know the Global Air Temperature Is Increasing?

A comprehensive analysis of changes in temperatures near the earth's surface and throughout much of the atmosphere is presented in the April 2006 CCSP Synthesis and Assessment Report 1.1 (Karl et al. 2006). This report addresses the nagging issue of differences in the rate of warming between measurements derived near the surface (typically 2 m above the surface) and those taken from higher in the atmosphere (i.e., the lower troposphere, or the atmosphere below roughly 12 km). The surface air temperatures are derived from several different analysis teams, using various combinations of ocean ships and buoys, land observations from weather reporting stations, and satellite data. Atmospheric data sets have been derived by using satellites, weather balloons, and a combination of the two.

Considering all the latest satellite, balloon, and surface records, the CCSP report concludes that there is no significant discrepancy between the rates of global temperature change over the past several decades at the surface compared with those higher in the atmosphere. The report does acknowledge, however, that there are still uncertainties in the tropics, related primarily to the data obtained from weather balloons. Many developing countries are struggling to launch weather balloons routinely and process their measurements, and it is unclear whether scientists have been able to adjust adequately for known biases and errors in the data.

Globally, data indicate that rates of temperature change have been similar throughout the atmosphere since 1979, when satellite data were first available, and that the rates of change have been slightly greater in the troposphere than on the earth's surface since 1958 (when weather balloons first had adequate spatial coverage for global calculations). The global surface temperature time series shown in Figure 2-3 indicates warming on even longer time scales, with acceleration since 1976.

Instrumental temperature measurements are not the only evidence for increasing global temperatures. The observed increased melting of glaciers can be used to estimate the rate of temperature increase since the late 19th century. Estimates of near-surface temperature based on glacial melting are very similar to estimates based on instrumental temperature data. A 15 to 20 percent reduction in Arctic sea ice since the 1970s, a 10 percent decrease in snow cover since the 1970s, and shortened periods of lake and river ice cover (about 2 weeks shorter since the 19th century) have been observed. Also, ocean heat content has significantly increased over the past several decades (IPCC 2007).

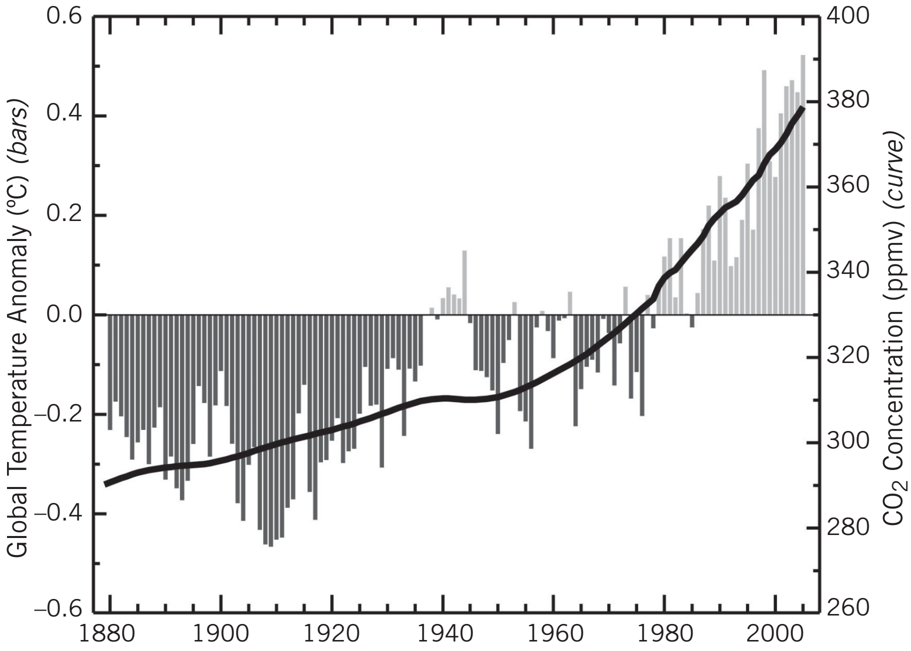

FIGURE 2-3 **Globally averaged surface air temperature and carbon dioxide (CO_2) concentration [parts per million by volume (ppmv)] since 1880.** Note that the shaded bars refer to global temperature anomalies and the solid line to CO_2 concentrations. (*Source:* Updated from Karl and Trenberth 2003.)

Why Do Scientists Think Humans Are Influencing the Earth's Climate?

Since the 1980s, the scientific community has been actively working on detecting climate change and determining how much of the change is attributable to human activities. As described above, one set of tools often used for detection and attribution is mathematical computer models of the climate. Outstanding issues in modeling include specifying forcing mechanisms (e.g., the causes of climate variability and change) within the climate system; addressing complex GHG feedback processes (e.g., methane and carbon) and properly dealing with indirect aerosol forcings and complex physical feedback processes (e.g., energy and water sources); and improving simulations of regional weather, especially extreme events. Today's inadequate or incomplete measurements of the various forcing mechanisms, with the exception of well-mixed GHGs, add uncertainty when one is trying to simulate past and present climate. Confidence in predicting future climate depends on using climate models to attribute past and present climate changes to specific causes. Despite these issues, a substantial and growing body of evidence (IPCC 2007) shows that climate models are useful tools for understanding the factors leading to climate change.

Recent CO_2 emission trends are upward, with increases of 0.5 to 1 percent per year over the past few decades. Concentrations of both reflective and nonreflective aerosols are also estimated to be increasing. Net positive radiative forcings[3] from GHGs dominate the net cooling forcings from aerosols, and the global temperature change over the past 25 to 30 years has exceeded the bounds of natural variability estimated from climate simulations with no human-caused changes. This has been the case since about 1980. As an example of how models are used to detect human influence on the climate system, Figure 2-4 shows that, without including all the known forcing mechanisms (natural and human or anthropogenic), the models cannot replicate observed global temperature changes. Moreover, many aspects of the climate system other than global surface temperatures have been tested for human influences.

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[3] Radiative forcing can be thought of as the change in heat flow [expressed in watts per square meter (W/m^2)] at the tropopause due to an internal change or a change in the external forcing of the climate system, such as a change in the concentration of CO_2 or the output of the sun. The tropopause is the boundary between the troposphere and the stratosphere, represented by a rather abrupt change from decreasing to increasing temperature with height.

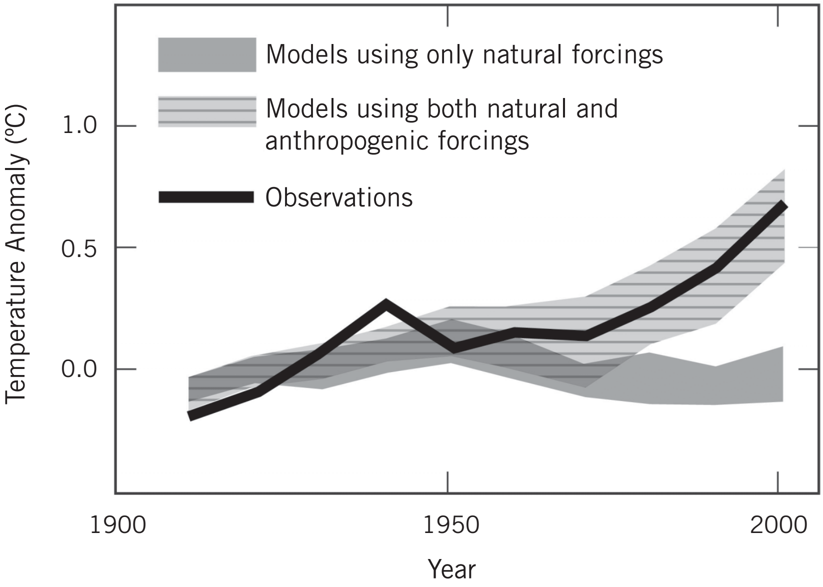

FIGURE 2-4 **Comparison of observed global change in surface temperature with simulations by climate models using natural and anthropogenic forcings.** Decadal averages of observations are shown for 1906 to 2005 (black line) plotted against the center of the decade and relative to the corresponding average for 1901–1950. Solid shading shows the 5 to 95 percent range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Banded shading shows the 5 to 95 percent range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. (*Source:* IPCC 2007, Figure SPM-4, p. 18. Reprinted with permission of the IPCC Secretariat, Geneva, Switzerland.)

Today there is convincing evidence from a variety of climate change detection and attribution studies pointing to human influences on climate. These studies include continental and subcontinental analyses of changes in temperature; the paleoclimatic[4] temperature record; three-dimensional analyses of changes in atmospheric temperature, in free atmospheric tem-

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[4] Climate during periods prior to the development of measuring instruments includes historical and geological time for which only proxy climate indicators are available. A proxy climate indicator is a local record that is interpreted, on the basis of physical and biophysical principles, to represent some combination of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies are tree ring records, characteristics of corals, and various data derived from ice cores.

perature, in sea ice extent and other components of the cryosphere, and in ocean heat content; and new studies on extreme weather and climate events. Thus, there is high confidence that the observed warming, especially during the period since the 1970s, is due mainly to human-caused increases in GHGs (Allen 2005; Gillett et al. 2002; Hegerl et al. 2001; IPCC 2007; Karl et al. 2006; Karoly and Wu 2005; Stone and Allen 2005; Stott et al. 2001; Tett et al. 2002; Zhang et al. 2006; Zwiers and Zhang 2003). How climate warming will be manifested over the next 50 to 100 years and which factors will have the greatest potential impact on transportation are discussed in the following section.

CLIMATE CHANGES RELEVANT TO U.S. TRANSPORTATION

Climate variability and change impact transportation mainly through changes in weather extremes, such as very hot days, very cold days, or severe storms; changes in climate extremes,[5] such as increases in the probability of intense precipitation events and extended droughts; and sea level rise. The U.S. transportation system was built for the typical weather and climate experienced locally, including a reasonable range of extremes, such as flooding events occurring as rarely as once in 100 years. Moderate changes in the mean climate have little impact on transportation infrastructure or operations because the system is designed to accommodate changing weather conditions. However, changes in weather and climate *extremes* can have a considerable impact on transportation, especially if they push environmental conditions outside the range for which the system was designed. Weather and climate extremes of relevance to transportation have been changing over the past several decades and are projected to continue to change in the future, with both negative and positive effects on the transportation system.

Table 2-1 lists the potential climate changes of greatest relevance for transportation, including the level of uncertainty associated with each. The following subsections address these changes in turn, largely summarizing the findings of a paper commissioned for this study (by Peterson

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[5] The exact threshold for what is classified as an extreme varies from one analysis to another, but an extreme event would normally be as rare as, or rarer than, the top or bottom 10 percent of all occurrences (CCSP 2007). For the purposes of this report, all tornadoes and hurricanes are considered extreme.

TABLE 2-1 **Level of Uncertainty Associated with Potential Climate Changes of Greatest Relevance to Transportation**

Potential Climate Change of Relevance to U.S. Transportation	Level of Uncertainty
Temperature	
Increases in very hot days and heat waves	*Very likely*
Decreases in very cold days	*Virtually certain*
Increases in Arctic temperatures	Virtually certain
Later onset of seasonal freeze and earlier onset of seasonal thaw	Virtually certain
Sea level rise	Virtually certain
Precipitation	
Increases in intense precipitation events	*Very likely*
Increases in drought conditions for some regions	*Likely*
Changes in seasonal precipitation and flooding patterns	Likely
Storms	
Increases in hurricane intensity	*Likely*
Increased intensity of cold-season storms, with increases in winds and in waves and storm surges	*Likely*

Note: Italicized uncertainty designations are those identified by IPCC (2007). Others reflect the committee's judgment, based on the available literature. IPCC (2007, 3) Working Group I established the following terminology to describe uncertainty, that is, probability of occurrence: *virtually certain,* ≥99 percent; *extremely likely,* ≥95 percent; *very likely,* ≥90 percent; *likely,* ≥66 percent; *more likely than not,* ≥50 percent; *unlikely,* ≤33 percent; *very unlikely,* ≤10 percent; *extremely unlikely,* ≤5 percent.

et al. 2006; see Appendix C). Each subsection highlights past trends, future projections, and key uncertainties. (The reader is referred to the paper by Peterson et al. 2006 for more detail and additional figures to support the discussion.) Note that the discussion generally progresses from those climate changes about which there is most certainty to those about which there is less.

Changes in Temperature

An increase in air temperature allows more water vapor in the atmosphere, which defines the upper bounds of the amount of precipitation that can occur during short-term (e.g., hourly to 1-day) extreme precipitation events. Surface moisture, if available (as it always is over the oceans), effectively acts as the "air conditioner" of the surface, as heat used for evaporation moistens rather than warms the air. Therefore, another consequence of global heating of the lower troposphere is accelerated land-surface drying and more atmospheric water vapor (the dominant GHG). Human-induced warming has been linked to the water vapor increases in both surface observations (Willett et al. 2007) and satellite observations over the oceans (Santer et al. 2007). Without an increase in precipitation, accelerated drying increases the incidence and severity of droughts (Dai et al. 2004), whereas additional atmospheric water vapor increases the risk of heavy precipitation events (Trenberth et al. 2003). Increases in global temperature also cause sea surface temperatures to rise, one of several important factors affecting hurricane intensity.

Changes in Temperature Including Extremes

U.S. temperatures have been rising over the past century, with more rapid increases since 1970 than earlier, as shown in Figure 2-5. It is unlikely that North American temperature changes since 1950 are due to natural climate variability alone (Karoly et al. 2003). The warming has not been uniform across the continent. In general, the western portion of the

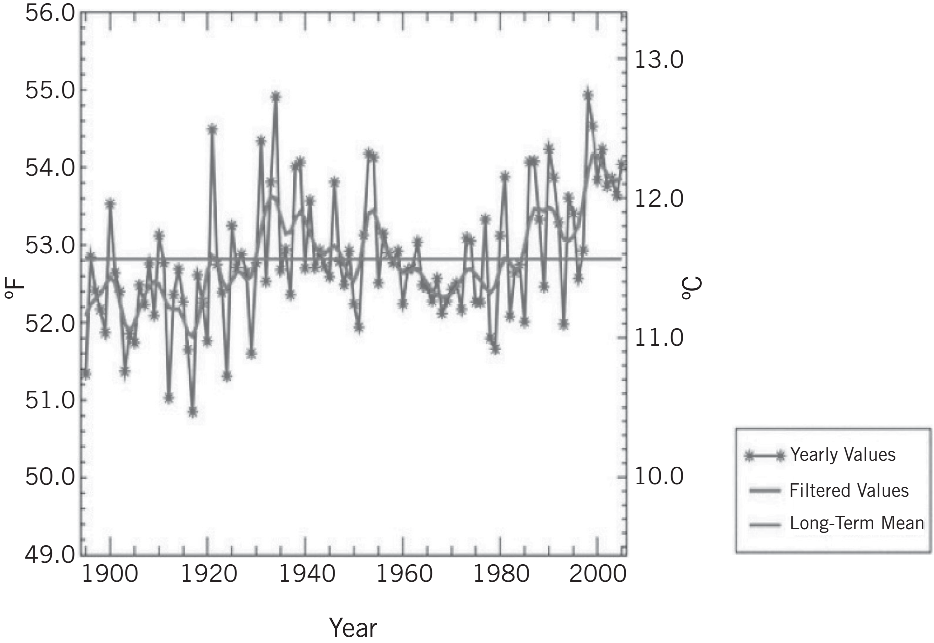


FIGURE 2-5 **Area-averaged mean temperature time series for the contiguous United States.** (*Source:* National Oceanic and Atmospheric Administration, National Climatic Data Center.)

contiguous United States has warmed more than the eastern portion. Alaska has warmed the most rapidly, with temperatures in some regions increasing by more than 0.6°C (1.1°F) per decade since 1970.

These warming trends are projected to continue over the next century on the basis of reasonable scenarios for future GHG emissions. Figure 2-6 shows the temperatures projected for the eastern United States for three different scenarios, each scenario having been run by multiple models. Other areas of the United States show similar warming trends [see Figure 6 in the commissioned paper by Peterson et al. 2006 (Appendix C)]. It is interesting to note that for the next 30 years, the uncertainties are primarily model related and not due to different emissions scenarios. Even if atmospheric concentrations remained at current levels, the models would still project similar warming over the next couple of decades (IPCC 2007).

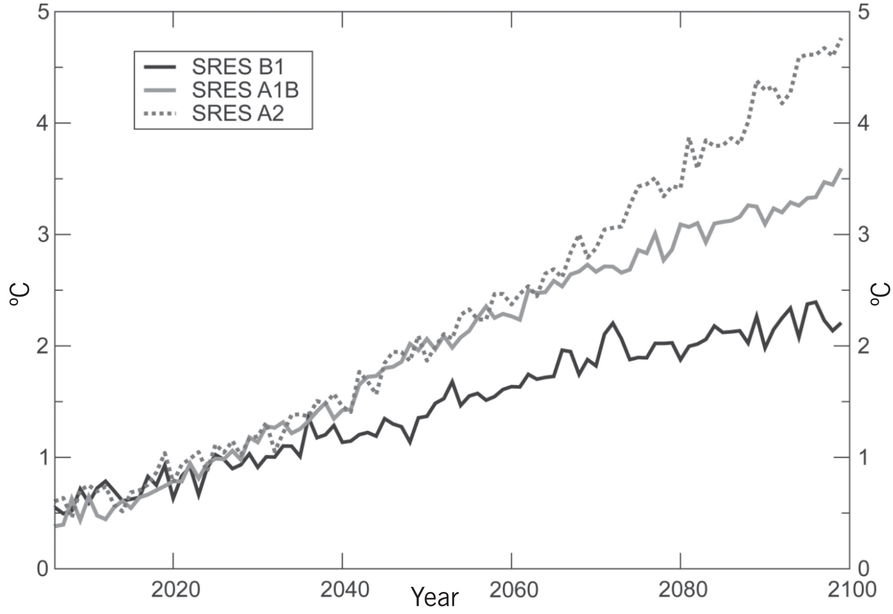


FIGURE 2-6 **Annual surface air temperature anomaly, from the 1990–1999 average, for the eastern United States and for three different emissions scenarios** (SRES = *Special Report on Emission Scenarios*). (*Source:* Peterson et al. 2006, Figure 5.)

Increases in Very Hot Days and Heat Waves

The next century is likely to bring more very hot days and heat waves [see Figure 9 in the paper by Peterson et al. 2006 (Appendix C)]. The number of days with temperature above 32.2°C (90°F) and 37.7°C (100°F) has been increasing since 1970, but it is not quite as high today as during the early 1950s, when several areas, particularly the south-central United States, had severe droughts. By 2090–2099, it is expected that the average temperature on the hottest day of the year will be 2.5°C to 4.5°C (4.5°F to 8.1°F) warmer than the hottest day of the year in the 1990s. Not only will there be hotter and more very hot days, but it is likely that the continental United States will have significantly more heat waves with sustained high temperatures for 5 consecutive days or longer.

There are several ways to conceptualize the change in very hot days. For example, the 20-year return value for the hottest day of the year in 2090–2099 can be compared with the same value for the 1990s. The 20-year return value is the temperature that is reached or exceeded on average once every 20 years over a long period of time. Such temperatures are truly rare events because they are expected to be reached only three or four times during the course of a human lifetime. Over most of the continental United States, the present-day 20-year return value temperatures would be reached or exceeded seven times or more in a 20-year interval by the end of the 21st century. Hence, the rare high-temperature event becomes commonplace in this scenario. Figure 2-7 depicts another way of considering the change in very hot days expected in the next century, with Dallas, Texas, as an example. The figure shows the probability of having 1 to 20 days during the summer when the temperature exceeds 43.3°C (110°F). The probability increases substantially 25, 50, and 90 years in the future. Similar plots are presented for Minneapolis, Minnesota, and Honolulu in the paper by Peterson et al. 2006 (see Appendix C).

Decreases in Very Cold Days

The number of very cold days has been decreasing in the United States since about 1970 (see Figure 2-8). This trend is also expected to continue into the future across the continent. For example, in the Washington, D.C., area, there is currently a 75 percent chance that 3 days each winter will have maximum temperatures at or below freezing. By the end of the century, this probability is projected to drop to 20 percent.

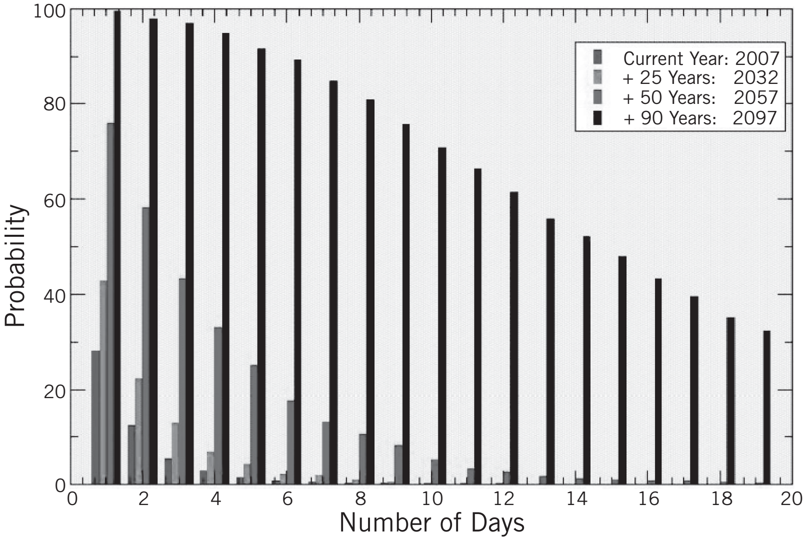


FIGURE 2-7 **Current and future probability of having 1 to 20 days during the summer at or above 43.3°C (110°F) in Dallas, Texas.** (*Source:* Peterson et al. 2006, Figure 10*b*.)

Later Onset of Seasonal Freeze and Earlier Onset of Seasonal Thaw

It is not just extremes of temperature that can have an impact on transportation. In particular, the number of days from the last freeze in the spring to the first freeze in the fall is expected to increase. Figure 2-9 shows a corresponding period—the length of time between the first day in the year that the maximum daily temperature reaches 21.1°C (70°F) and the last day of the year when this occurs. This interval has been increasing since 1970 and can be expected to increase further in the future. While there is considerable year-to-year variability in the number of freeze–thaw days (i.e., days when an observation station's maximum temperature is above freezing and its minimum temperature below freezing), no distinct trend has been observed in this quantity.

Changes in Sea Level

Sea level is projected to rise over the next century, but there is significant uncertainty as to how much and how fast. The IPCC Third Assessment Report includes a range of estimates that sea levels will rise 0.1 to 0.9 m above 1990 levels by 2100 (IPCC 2001). To put this in context, the IPCC

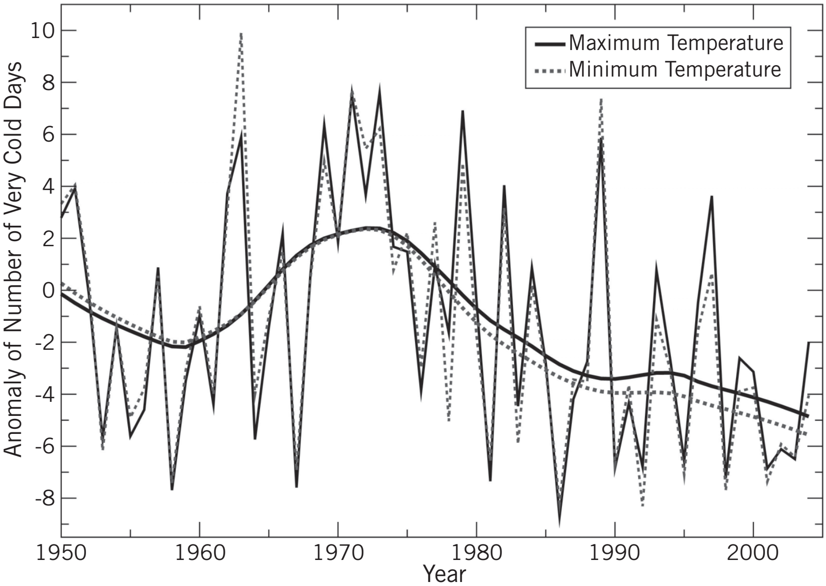


FIGURE 2-8 **U.S. nationally averaged anomaly of the number of days at or below the coldest 10 percent of January maximum and minimum temperatures at each station (percentiles were calculated on a 1961–1990 base period).** (*Source:* Peterson et al. 2006, Figure 14.)

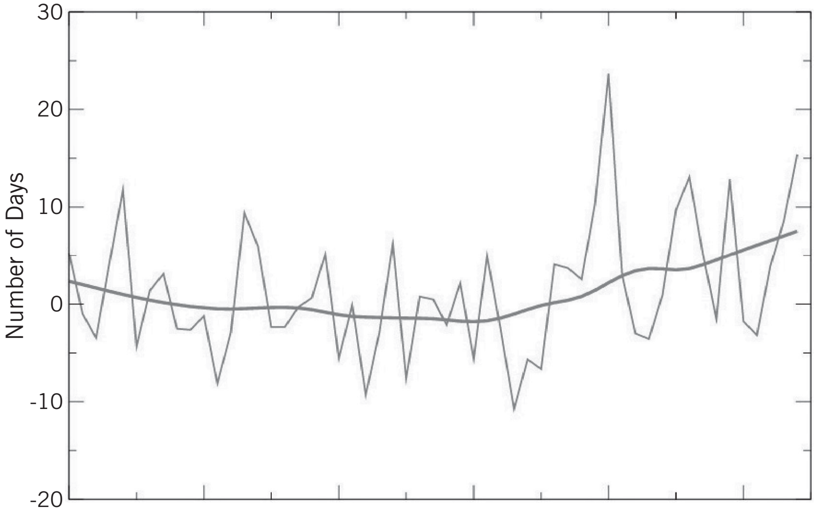


FIGURE 2-9 **U.S. area-averaged anomaly of the length of time between the first day above 21.1°C (70°F) in the spring and the last day above 21.1°C in the fall.** (*Source:* Peterson et al. 2006, Figure 19.)

estimates that during the past 6,000 years, global average sea level variations on time scales of a few hundred years and longer are likely to have been less than 0.3 to 0.5 m. Observed sea level changes from tide gauges and satellite altimeters indicate that the 1993–2005 rate of sea level rise was 3 mm per year (Church and White 2006). If this linear trend continues, sea level will rise by about 0.3 m by the end of the 21st century. Several analyses have identified a number of factors that as yet have uncertain likelihoods but could easily contribute to nonlinear and abrupt rises in sea level (IPCC 2007; Schoof 2007; Vaughan et al. 2007). Such extrapolations are tentative, however, because the extent to which the trends of the past decade are due to natural variability in the climate system is unknown.

Global warming affects sea level through two mechanisms: thermal expansion of seawater and melting of ice present on land surfaces. Other factors also play a role in sea level, such as the amount of water held back by human-made land reservoirs, leading to sea level falls, but these factors are less important. There are still problems in reconciling the observed changes of the past century with the estimated contributions from these different sources (Munk 2002). Most of the projected sea level rise is due to thermal expansion, but should the melting of the polar ice caps accelerate, sea level would rise much higher. The rapid melting of Greenland, which would have a very large impact, is possible, but too little is known to assess its likelihood (IPCC 2007). Current model projections of sea level rise are based on the observed rate of melting during 1993–2003, but these rates could increase or decrease in the future.

More important to transportation than the global change in sea level is the local apparent change in sea level (Burkett 2002; Titus 2002). Estimates of local apparent sea level rise take into account the vertical movement of land and coastal erosion. Coastal erosion, in turn, is driven by sea level rise. To estimate local sea level rise, land subsidence in the Gulf Coast and uplift along the New England coast are important factors (NRC 1987). Figure 2-10 illustrates that because of these factors, different regions can have quite different local sea level rise.

Impacts of Sea Level Rise on Shoreline Location

Predicting rates of shoreline retreat and land loss is critical to planning future coastal infrastructure. According to the Bruun rule, shorelines

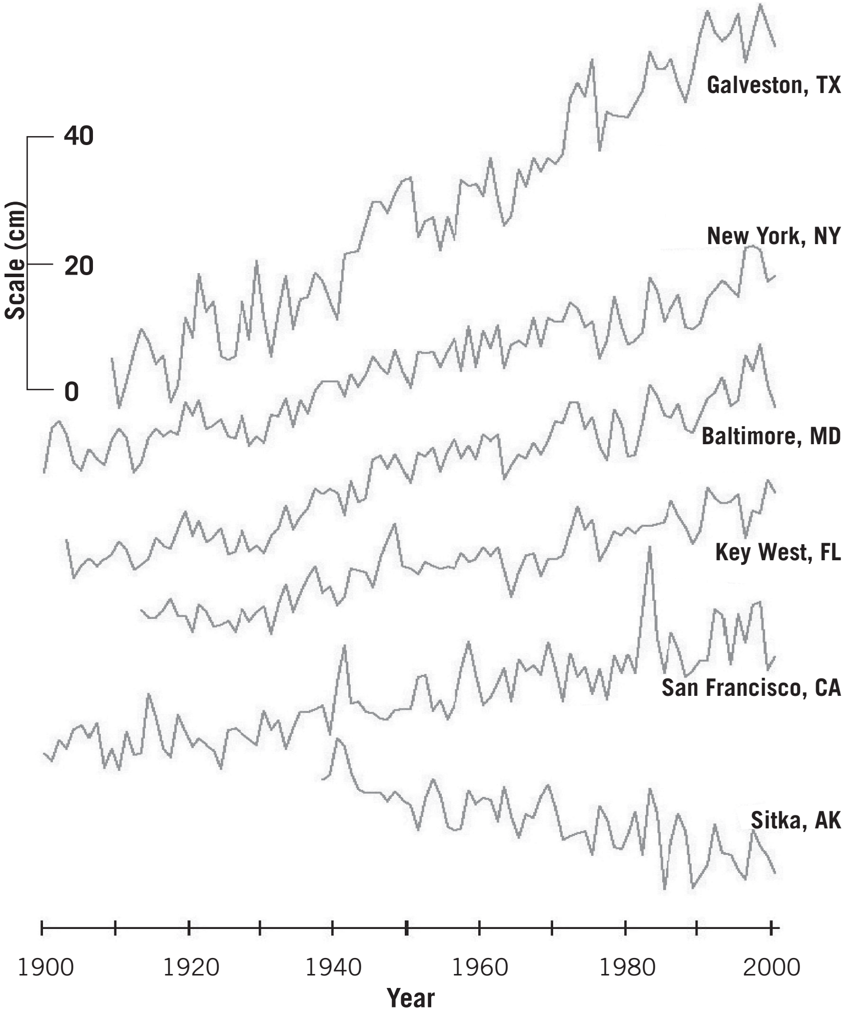


FIGURE 2-10 **Trends in sea level from global changes in seawater volume and local changes in land surface elevation for representative locations in the United States.** (*Source:* NOAA 2001, p. 4.)

retreat so as to maintain a constant slope, and by some estimates, move inland roughly 150 m for every meter rise in sea level (Bruun 1962; Leatherman et al. 2000). Thus, for a 0.5-m worldwide sea level rise, sandy shores could retreat 75 m. Although the Bruun rule is useful as a conceptual model, rigorous application of coastal geology and climatology models is necessary for risk analysis at specific locations.

Exacerbation of Storm Surge by Sea Level Rise

Storm surge is the abnormal rise in sea level accompanying a hurricane or other intense storm, above the level of the normal or astronomic tide. Storm surge can be exacerbated by tidal piling, a phenomenon of abnormally high water levels from successive incoming tides that do not completely drain because of strong winds or waves persisting through successive tide cycles. Flooding due to coastal storms results from a combination of storm surge and intense precipitation. Storm surge is of great concern to port operations, mooring facilities, and moored vessels, as well as to coastal infrastructure that is vulnerable to flooding.

Storm surge has been estimated or modeled by using the United States Army Corps of Engineers' Waterways Experiment Station model; the National Weather Service's Sea, Lake, and Overland Surge from Hurricanes model; and more recently the Advanced Circulation Model (ADCIRC) (Westerink et al. 1994). These models use wind fields from past storms as input; these historical input data are updated infrequently. When updated, these models show wider areas of 100-year floodplains. For example, a recent analysis with the ADCIRC model using input data through the 2005 hurricane season showed greater storm surge and higher flooding. The magnitude of the 100-year storm surge flood (previously established using data for 1900–1956) would now recur at an interval of 75 years on the basis of data for 1900–2005 (Levinson 2006).

Changes in Precipitation

Changes in the Intensity of Heavy and Extreme Precipitation

Basic theory and climate model simulations as well as empirical evidence (see Figure 2-11) confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when total precipitation remains constant, with prospects for even stronger events when precipitation amounts increase. Figure 2-12 depicts the aggregate land-

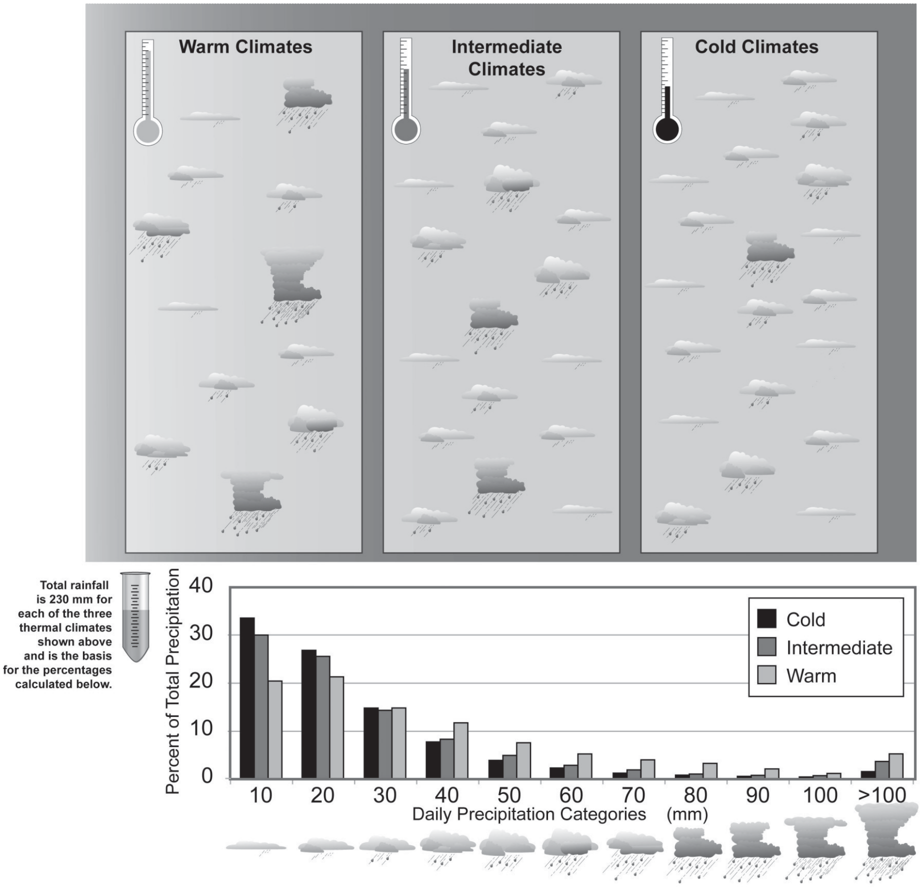


FIGURE 2-11 **Diagram showing that warmer climates have a higher percentage of total rainfall coming from heavy and very heavy events.** The data are based on a worldwide distribution of observing stations, each with the same seasonal mean precipitation amount of 230 (±5) mm. In cool climates, there are more daily precipitation events than in warmer climates (adapted from Karl and Trenberth 2003). The various cloud and rain symbols reflect the different daily precipitation rates and are categorized in the top panel of the figure to reflect the approximate proportion of the different rates for cool, moderate, and warm climates across the globe.

surface worldwide changes in intense precipitation events over the last half of the 20th century, with an associated geographic depiction of where changes in intense precipitation have occurred; most areas show increases. Worldwide, an increase of a few percent in intense precipitation events is evident since the middle of the 20th century, particularly in the middle and

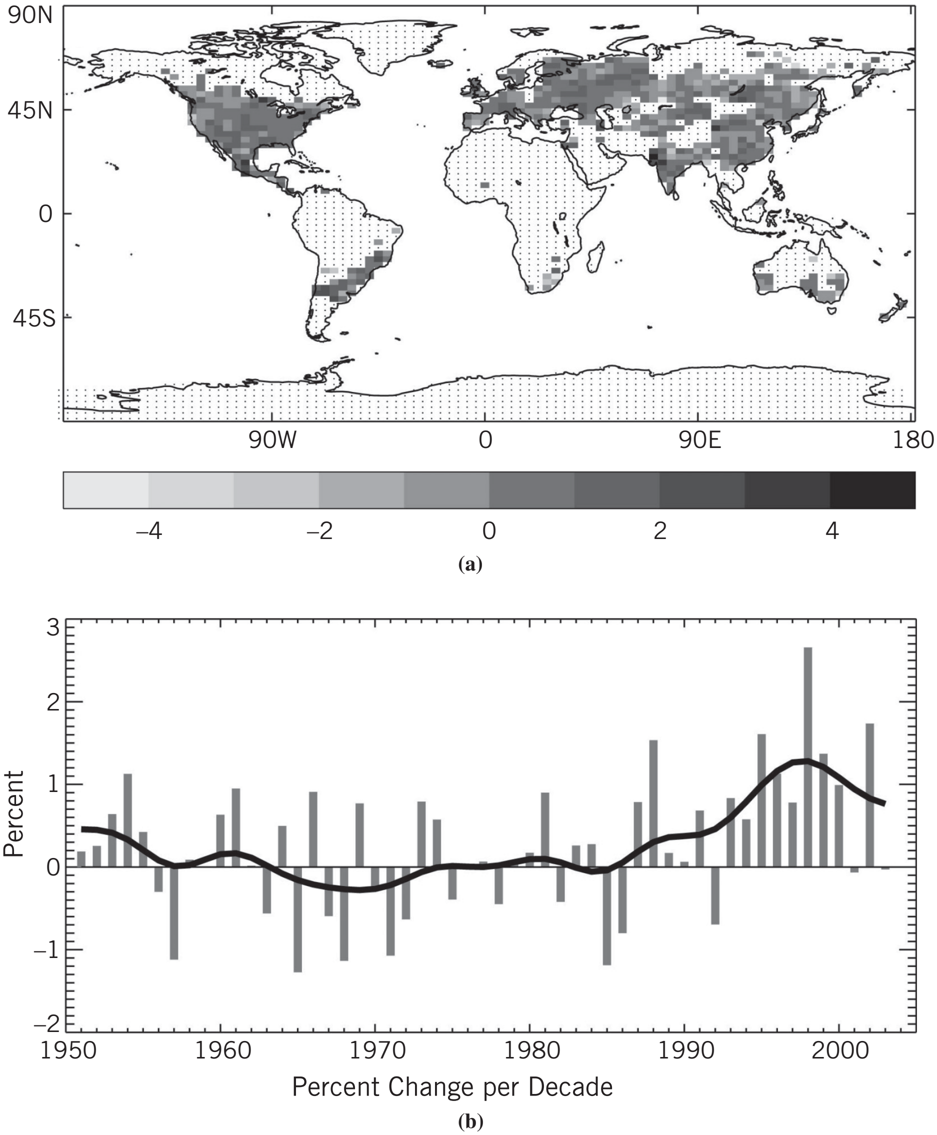
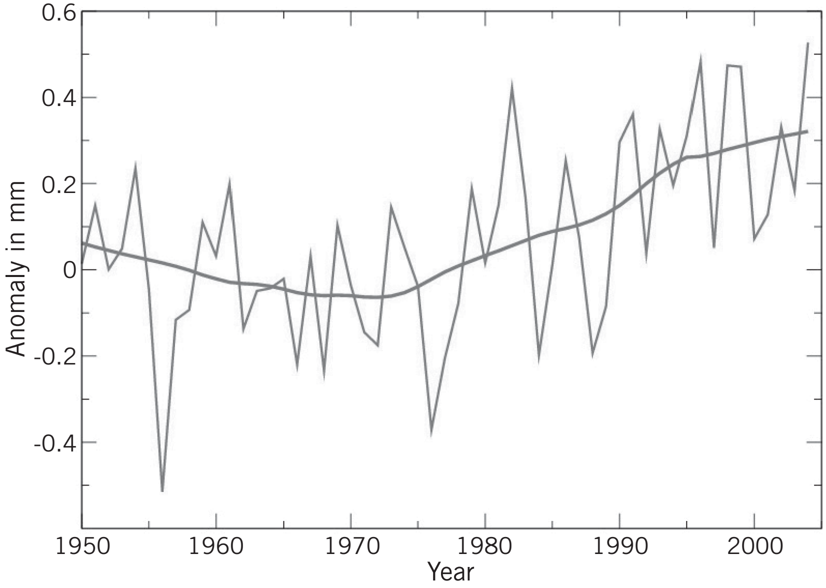


FIGURE 2-12 **Trends in the contribution to total annual precipitation from very wet days (95th percentile) in percent per decade: (*a*) regional changes, with stippled areas not reporting; and (*b*) worldwide changes in areas with adequate data.** Percentiles were calculated on the basis of 1961–1990 data. [*Source:* Alexander et al. 2006. (Copyright 2006 by American Geophysical Union. Reproduced with permission of American Geophysical Union in the format Other book via Copyright Clearance Center.)]

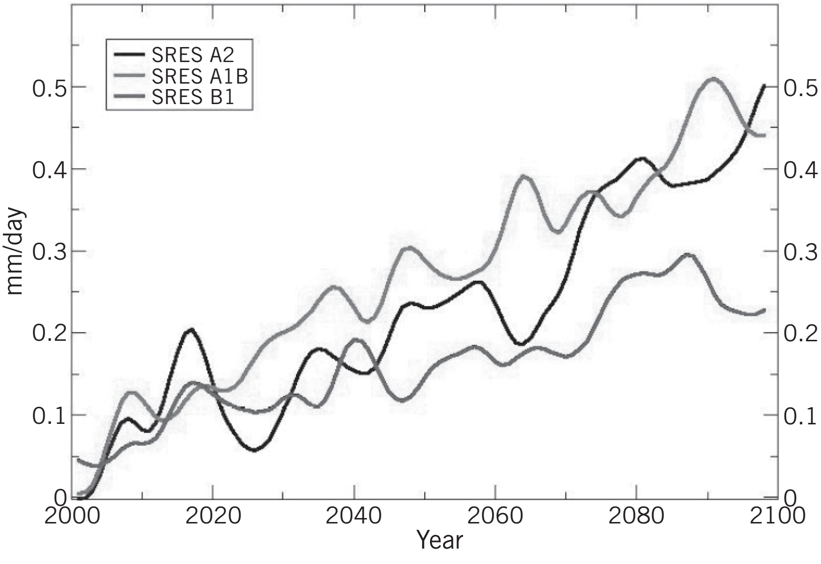
high latitudes. This leads to more frequent events that are currently rare. For example, by the end of the 21st century, a conservative projection of climate change has the recurrence period (or average expected waiting time) for the current 1-in-20-year, heaviest daily precipitation event reducing to every 6 to 8 years over much of North America (Kharin et al. 2007; Wehner 2005).

The practical implications of addressing these changes are seen in the National Oceanic and Atmospheric Administration's (NOAA's) recent update of the Ohio River Basin's 100-year daily precipitation return period. These data are used to help set engineering design standards related to excessive rainfall. Over the past several decades, increases in the amount of precipitation occurring during the heaviest daily precipitation events have been observed in many areas of the central and eastern United States (Groisman et al. 2004; Groisman et al. 2005; Karl and Knight 1998). In fact, over the 20th century, annual precipitation averaged across the United States increased by about 7 percent, but very intense precipitation events (above the 95th percentile) increased by nearly three times that rate (20 percent). The observed behavior supports one of the most confident projections that scientists can make about future precipitation. Considerable analysis has shown that because water vapor has increased in the atmosphere and will continue to do so with added anthropogenic GHG emissions, the intensity of precipitation will continue to increase in much of the United States (and elsewhere). In many regions of the world, increases in extreme precipitation are occurring even when total precipitation is relatively constant (Alpert et al. 2002; Groisman et al. 2003; Groisman et al. 2005). In areas where overall precipitation increases, the increase in the intensity of very heavy precipitation events will be even greater.

There are several different ways to think about how the increase in the intensity of heavy and extreme precipitation events might be manifested. One option is to consider changes in a 20-year return event. In the A1b emissions scenario, the present-day 20-year precipitation event would take place 2 to 4 times as frequently by the end of the 21st century [see Figure 27*c* and text in Peterson et al. 2006 (Appendix C) for an explanation of the emissions scenarios]. Another useful measure is the Simple Daily Intensity Index, which equals the total annual precipitation divided by the number of days with precipitation in that year. Figure 2-13*a* shows that this quantity has increased over the United States, indicating that on days that precipitation



(a)



(b)

FIGURE 2-13 **(*a*) Upward trend in the Simple Daily Intensity Index (i.e., total precipitation per year divided by the number of days with precipitation) indicating that, on a U.S. area-averaged basis, when precipitation does occur, it tends to be heavier. (*b*) Median model-projected changes in the Simple Daily Intensity Index for the continental United States.** (*Source:* Peterson et al. 2006, Figures 28*a,* 28*b.*)

does occur, the amount is becoming greater. Median model projections for the future over the continental United States (Figure 2-13*b*) indicate that the Simple Daily Intensity Index is expected to continue to increase over the next century.

Changes in the Severity and Frequency of Drought

Drought is a recurring feature of the climate system; major droughts have occurred in the past and are expected in the future. At any given time, at least part of the United States is in drought, with proportions ranging from 5 to 80 percent of the nation's total land area. U.S. droughts show pronounced multiyear to multidecadal variability, but there is no convincing evidence for systematic long-term trends toward more or fewer events. Drought calculations have shown that over the United States, the increase in temperatures that may have led to increased evaporation has been compensated by a general increase in precipitation during the past few decades (Dai et al. 2004), with the result that there has been no general trend in drought intensity nationwide (Figure 2-14). Over the United States, climate model projections of precipitation change by the end of the 21st century show a tendency for increasing winter precipitation and decreasing summer precipitation as global temperatures increase. Locations that do experience decreased precipitation in addition to the continuing increase in temperatures, such as the recently observed record-high January–June of 2006 (NOAA 2006), could have greater drought severity and frequency, especially during periods of dry weather due to increases in evaporation. Long-term warming trends have already led to changes in the timing of snowmelt and stream flows, especially in the West, resulting in earlier peak stream flows and diminished summertime flows.

For the continental United States, the most extensive drought in the modern observational record occurred from 1933 to 1938. In July 1934, 80 percent of the United States was gripped by moderate or greater drought (see Figure 2-14), and 63 percent was experiencing severe to extreme drought. During 1953–1957, severe drought covered up to 50 percent of the country. Paleoclimatic data (e.g., tree ring measurements) have been used to reconstruct drought patterns for the period prior to the modern instrumental record (Cook et al. 1999; Cook et al. 2004). These reconstructions show that during most of the past two millennia, the climate of the western United States has been more arid than at present. The recent intense western drought from 1999 to 2004 that strongly affected the Colorado

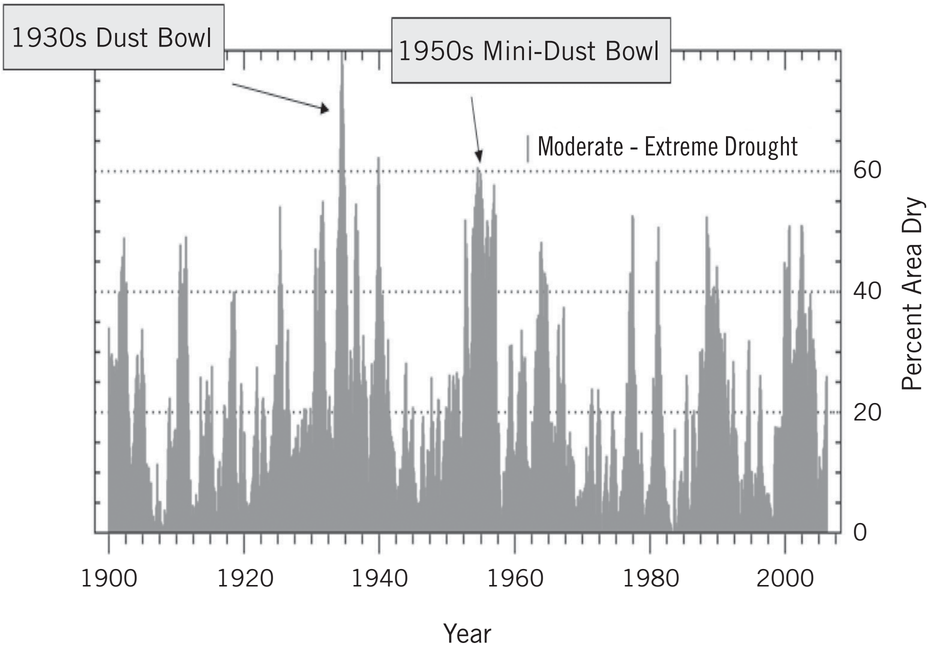


FIGURE 2-14 **Percentage of the contiguous U.S. land area in moderate to severe drought, January 1900–March 2006, based on the Palmer Drought Index.** (*Source:* NOAA, National Climatic Data Center.)

River basin was exceeded in severity as recently as the 19th century. Within the past millennium, severe droughts in both the western United States and the Midwest have occurred that have lasted for multiple decades.

One of the more robust findings of the IPCC (2007) relates to recent agreement among virtually all climate model simulations of the 21st century that a drying of the southwestern United States is evident. Seager et al. (2007) provide the details and indicate that this drying is attributable to both an increase in evapotranspiration and reduced precipitation. Droughts in this part of the country that occur naturally, such as those of the past two millennia, would be expected to be enhanced as a result of greenhouse forcing of the climate. Increased temperatures will lead to increased drying during periods of dry weather, leading to more intense droughts in much of the United States. For the southwestern United States, reduced precipitation will add to this effect.

Changes in Storms

Changes in Hurricane Intensity and Frequency

Tropical storms, particularly hurricanes, are an important issue of concern for the United States. The record-breaking hurricane season of 2005, especially the havoc created by Katrina, raised public awareness of the dangers of hurricanes to new heights. Hurricanes respond to a number of environmental factors, including ocean temperatures, atmospheric stability, wind changes, El Niño, and others. One important question is whether hurricane activity has changed over the past 100 years. Since 1995, Atlantic hurricane activity has increased substantially, with more and more intense hurricanes, compared with the previous two decades, and this increased level of activity is also reflected in those hurricanes striking the United States (see Figure 2-15). Earlier periods, however, such as 1945–1970, were nearly as active.

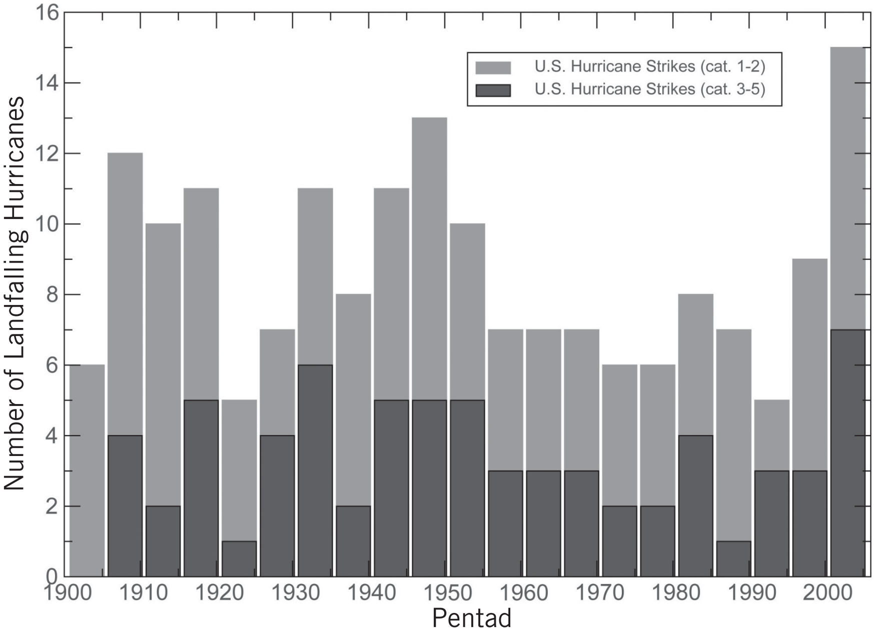


FIGURE 2-15 **Number of hurricanes striking the United States, 1901–2005, summed by 5-year periods** (e.g., 1901–1905, 1906–1910). The black bars represent the number of major hurricanes (Category 3–5) and the gray bars the number of weaker Category 1 and 2 hurricanes per 5-year period (pentad). (*Source:* NOAA, National Climatic Data Center.)

An important consideration with regard to hurricane intensity is the trend toward warmer sea surface temperatures, particularly in the tropical Atlantic and the Gulf of Mexico, indicating that climate change may play some role in increased hurricane intensity (Emanuel 2005; Webster et al. 2005). Another factor is a slow cycle of natural fluctuations in atmospheric conditions and ocean temperatures in the North Atlantic, referred to as the Atlantic Multidecadal Oscillation, which is currently in a warm ocean temperature phase.

What does the future hold for hurricane activity? In the near term, it is expected that favorable conditions for Atlantic hurricanes will persist for the next decade or so on the basis of previously active periods. For the longer term, climate models project an increase in the intensity of strong hurricanes in the 21st century (Bengtsson et al. 2007; McDonald et al. 2005; Oouchi et al. 2006; Sugi et al. 2002). Specifically, this translates to increases in wind speed and about a half-category increase in intensity on the commonly used Saffir-Simpson Hurricane Intensity Scale as tropical sea surface temperatures increase by nearly 2°C. Given these conditions (stronger hurricanes and warmer tropical sea surface temperatures), climate models also predict an increase in storm rainfall rates of about 20 percent (T. R. Knutson, personal communication, 2006). No robust projections concerning the annual global number of tropical storms have yet emerged from modeling studies, but more detailed analyses focused on the Atlantic Ocean suggest no significant increases in the annual number of Atlantic tropical storms (CCSP 2007). Many relevant factors, such as future changes in wind field patterns, remain very difficult to predict.

Extratropical Storms

The IPCC AR4 models projected a reduction in the total number of midlatitude cyclones and an increase in the number of intense storms. This is a robust result, yielded by essentially all the models (Lambert and Fyfe 2006). Associated with these changes is an increase in ocean wave height in the northeastern Atlantic and the northern Pacific (Wang et al. 2004). Analysis of the conditions that cause thunderstorm systems in the United States to produce hail results in a time series fairly similar to the U.S. temperature time series shown in Figure 2-5, decreasing from 1950 to the 1970s and then increasing (Brooks and Dotzek 2008). Projecting these conditions into the future is difficult because contemporary climate models lack sufficient resolution to simulate these storms directly.

Visibility

Some of the climate changes discussed earlier in this chapter may have secondary effects. Visibility is one such effect. For example, if the number of intense extratropical storms increases, they may be accompanied by more time with low visibility during heavy snowfall events (Rasmussen et al. 1999). Projections of drying in the interior of continents would imply the possibility of increases in blowing dust. The risk of forest wildfires in the American West is strongly associated with increased spring and summer temperatures and an earlier spring melt (Westerling et al. 2006) as well as possible biomass increases from increased precipitation (e.g., Bachelet et al. 2001; Lenihan et al. 2003). These are exactly the conditions being projected by models for the future. Therefore, wildfire-induced decreases in visibility are likely to become more frequent. It is uncertain from a theoretical standpoint how the occurrence of fog might change in a warming climate. Therefore, while the number of low-visibility events associated with intense storms and fires might be projected to increase, it is uncertain whether the total number of occurrences of low visibility would increase, decrease, or remain the same in the projected climate of the future.

Transportation is significantly affected when visibility drops to less than about 400 m (0.25 mi). Times with such low visibility are associated primarily with fog, heavy precipitation, blowing sand or snow, or smoke from wildfires. Observations of past trends in visibility and models of changes projected for the future are not currently available. While visibility is observed at airports throughout the United States, changes in observing practices over the past decades make it inappropriate to examine long-term changes in low visibility without a major effort to assess the data's homogeneity.

Climate Considerations Related to Alaska

The Alaskan Arctic and sub-Arctic are recognized as the area of the world where changes to the climate are likely to be among the greatest, leading to significant impacts. In addition, the area has always experienced great natural climatic variability. Because the climate changes in Alaska are so distinct from those in the rest of the United States, this section is devoted to an examination of these expected changes as they relate to transportation.

Climate variables of particular relevance to the transportation sector in Alaska include (*a*) the extent of sea ice, snow cover, and permafrost, all directly driven by temperature change and to some extent by atmospheric and oceanic circulation; (*b*) storminess as related to wave height and storm surges; (*c*) precipitation and related snow and ice cover; and (*d*) sea level as related to land ice, ocean temperature, and movement of the land relative to the ocean due to geologic features and glacial rebound of the land as land ice melts.

Generally, the extent of sea ice is important because the ice dampens the energy of ocean waves. Wave energy is dependent on the distance traveled by the wind over open water. Less extensive sea ice exposes the coastline to more frequent and potentially higher ocean waves and swells. Temperature drives the extent of sea ice, but changes in atmospheric and ocean circulation also play an important role in multiyear variations in the extent and location of sea ice. Changes in the type, amount, and intensity of precipitation, as well as the extent of snow and ice cover, can also contribute to coastal erosion from stream flow and overland runoff to the sea. Loss of permafrost along coasts can lead to subsidence of the land, which occurs when ice beneath the sea and along the shoreline melts. Alaska has considerable permafrost along its northern and western coasts. The height of the sea relative to the land is the ultimate long-term driver of coastal erosion, but Alaskan sea level rise is complicated by both climatic factors and geologic forces, affecting local and regional changes in the height of the land relative to the ocean.

Atmospheric Temperature

Temperatures in Alaska have increased. Observational data indicate that Alaskan spring and summer surface temperatures have increased by about 2°C to 3°C (about 4°F to 5°F) in the past few decades. However, there are no discernible trends in temperature during autumn, and changes in winter temperature are more complex. There were two 5-year periods in the first half of the 20th century when temperatures were nearly as warm as today, but record-breaking high temperatures have become more common during recent decades.

Most climate model projections for temperature change during the 21st century suggest that Alaska, and the Arctic as a whole, will warm at least twice as much as the rest of the world. The warming is expected to be greatest during the cold half of the year. The observed lack of warming during the autumn and the relatively large increases during other times of the year are not entirely consistent with model projections; they do not depict this asymmetry.

As temperatures increase and sea ice continues to melt, a natural climate feedback occurs as a result of less reflection of sunlight by the ocean formerly covered by sea ice. This feedback can lead to accelerated warming and additional sea ice melting. At present, the rate of loss of Northern Hemisphere sea ice is exceeding climate model projections, and at the present rate of loss, summer sea ice will be absent before the middle of this century. Climate models do project an acceleration of sea ice retreat over the 21st century, with periods of extensive melting lasting progressively further into spring and fall. All climate models project this trend to continue regardless of the emission scenario used and the sensitivity of the model.

Large portions of Northern Hemisphere sea ice form during the cold seasons and melt during the warm seasons. Considerable sea ice persists through the melt season, but because of ocean circulation and the resultant ice movement, multiyear sea ice makes up only a fraction of the total ice extent. Records indicate that the formation of new sea ice each year cannot keep pace with the rate of melting, which is consistent with observed surface warming. Northern Hemisphere sea ice has been decreasing steadily since the 1950s, measured largely through continuous coverage provided by NOAA polar orbiting satellites beginning in the 1970s. Prior to that time, assessment of the extent of Northern Hemisphere sea ice during the first half of the 20th century was limited to reports from land stations and ocean surface observations. Scientists have less confidence in the data for the first part of the century, but independent anecdotal evidence, such as interviews with native peoples of Alaska, also suggests substantially greater extent of sea ice earlier in the century.

It is important to understand trends in the extent of coastal sea ice because it is an important determinant of wave energy affecting coastlines. As the storms that create wave energy also exhibit strong seasonal variation, it is important to know how sea ice is changing by season. Since the 1950s, the extent of sea ice during winter and autumn has decreased from 15 million square kilometers (km^2) to 14 million km^2 and from 12 million km^2 to 11 million km^2, respectively. Since the 1950s, decreases in spring and summer have been substantially greater, down from an average of 15 million km^2 to 12 million km^2 and 11 million km^2 to 8 million km^2, respectively. This is equivalent to more than 10 percent of the North American land mass and is an area larger than the state of Alaska.

Extratropical Storms

The climatology of Pacific Ocean storms favors the development of the strongest storms (extratropical cyclones) from autumn to spring. Although there are remaining uncertainties about the quality of the data, analyses of Pacific Ocean extratropical cyclones over the past 50 years indicate little change in the total number but a significant increase in the number of intense storms (those with low central pressure and resultant high winds and waves). The increase in extratropical storms is punctuated by considerable year-to-year variability. Both observational evidence and modeling projections support the notion that as the world warms, the intensity of cyclones in the northern Pacific (and the northern Atlantic) will increase (e.g., Lambert and Fyfe 2006; Wang et al. 2006).

Even without an increase in storm intensity, the greater expanse of open water due to less extensive sea ice means that ocean waves, with resultant coastal erosion, can occur more frequently and with greater impact.

Precipitation and Extent of Snow Cover

One of the most difficult quantities to measure across the state of Alaska is precipitation. This is the case because of the variable nature of precipitation in general, the relatively low number of observing stations across the state, and the difficulty of providing high-quality data in the harsh Arctic environment. The large uncertainty in estimated precipitation trends is also due to the difficulty of measuring wind-blown solid precipitation.

On the basis of existing records, however, there is evidence to indicate that during the past 40 years, as temperatures have warmed, more precipitation has been falling in liquid form (rain) as opposed to solid form (snow, ice). The quantity of precipitation also increased during the 20th century, with much of that increase occurring during the recent period of warming over the past 40 years. The increase is estimated to be between 10 and 20 percent, with most of it occurring during the summer and winter rather than during the transition seasons. Because of greater overall precipitation in the summer, the percent increase in summer equates to a greater quantity of precipitation compared with winter.

Analyses of changes in intense precipitation events have been conducted for areas south of 62°N latitude. They show that the frequency of intense precipitation events has increased substantially (30 to 40 percent) during the past several decades. Thus, a disproportionate amount of the precipitation increase is attributable to the most intense precipitation events.

Climate models project that precipitation will increase by a greater proportion in the high latitudes compared with the rest of the world. This result is consistent from model to model, as is the fact that this increase is expected to be disproportionately larger in the more intense precipitation events. Both of these phenomena can lead to increased erosion.

NOAA's polar-orbiting environmental satellite data and surface-based observations have also revealed major changes in the extent of snow cover. The extent of North American snow cover has decreased by about 1 million km^2, and this trend is expected to continue or accelerate. Surface observers also report a 1- to 2-week reduction in the number of days with snow on the ground across the state. In addition, in the Arctic, the lake and river ice season is now estimated to be 12 days shorter than in the 19th century.

The increase in total and liquid precipitation, especially when falling on less extensive snow cover, can affect soil erosion. However, the complex effects of changes in precipitation type and intensity, earlier breakup of winter ice, and less extensive snow cover have not been well evaluated with respect to potential impacts on coastal erosion and flooding. It will be necessary to know which factor dominates in order to understand whether coastal erosion and flooding will be enhanced or ameliorated as a result of changes in the extent of precipitation and snow cover.

Permafrost

Thawing of the permafrost, especially along the northern coasts, is expected to continue. Long-term measurements of temperatures within the permafrost are rare, but it is clear that as air and ocean temperatures have warmed, permafrost has been melting. As permafrost melts along the coastlines, the effect on coastal erosion can be compounded by the retreat of sea ice. The thaw causes the land to subside along the shore, exposing more land to the action of the waves. The thaw also causes slumping and landslides in the interior, undermining structures built on or near permafrost.

Sea Level

A general increase in sea level would expose more land to coastal erosion through wave energy and storm surges. However, it is important to recognize that there are many local and regional variations in sea level rise, and Alaska is no exception in this regard. Complications arise because of geologic forces; the rebound of the land as glaciers melt; and in some areas, local engineering projects. For certain areas in Alaska (e.g., parts of southeast Alaska), sea level is actually falling as a result of natural geologic and glacial rebound effects, but this is generally not the case in much of the state. It is clear, however, that changes in Alaskan climate are among the greatest in the world. They have likely played an important role in determining the extent of coastal erosion and flooding in the state and are likely to continue to do so in the future. Accelerated coastal erosion and flooding linked to sea level rise in Alaska cannot be ruled out.

FINDINGS

The state of the science continues to indicate that modern climate change is affected by human influences, primarily human-induced changes in atmospheric composition that are warming the climate. These changes result mainly from emissions of GHGs associated with energy use, but on local and regional scales, urbanization and land use changes are also important contributors to climate change. Once in the atmosphere, GHG concentrations have a long residence time—on the order of a century. Thus, they would continue to affect climate conditions even if GHG emissions were eliminated today, and they demand a response.

Substantial progress has been made in monitoring and understanding the causes of climate change, but scientific, technical, and institutional challenges to improving projections of future climate change remain. For example, considerable uncertainty persists about the rates of climate change that can be expected during the 21st century. Nevertheless, it is clear that climate change will be increasingly manifested in important and tangible ways, such as changes in extremes of temperature and precipitation, decreases in seasonal and perennial snow and ice extent, and rising sea levels. In addition, climate models project an increase in the intensity of strong hurricanes, with an increase in related storm rainfall rates, in the 21st century. Thus, as human-induced climate changes are superimposed on the natural variability of the climate, the future will include new classes of weather and climate extremes not experienced in modern times.

Climate changes will affect transportation largely through these extremes. The U.S. transportation system was built for the typical weather and climate experienced locally, including a reasonable range of extremes. If projected climate changes push environmental conditions outside the range for which the system was designed—and the scientific evidence suggests that this will be the case—the impacts will be significant. They will vary by mode of transportation and region of the country, and some will be positive; in general, however, the impacts will be widespread and costly in both human and economic terms and require significant changes in the planning, design, construction, operation, and maintenance of transportation systems. In the next chapter, the likely impacts of projected climate changes on transportation are examined in detail.

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Abbreviations

CCSP	U.S. Climate Change Science Program
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council

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3

Impacts of Climate Change on Transportation

This chapter explores what is known about the potential impacts of climate change on transportation. First, the vulnerability of the transportation system to climate change is considered, recognizing, however, that not all changes will have negative impacts. Then, the potential impacts of the major climate change factors of relevance for U.S. transportation identified in the previous chapter are described for each transportation mode. Next, the few studies that have actually assessed the impacts of climate change on transportation in a particular region or metropolitan area are reviewed; these studies provide a good illustration of regional differences in both expected climate changes and impacts. The chapter ends with the committee's findings on the impacts of climate change on transportation.

VULNERABILITY OF THE TRANSPORTATION SYSTEM TO CLIMATE CHANGE

No comprehensive inventory exists of U.S. transportation infrastructure vulnerable to climate change impacts, the potential extent of that exposure, or the potential damage costs. Nevertheless, some salient data can be pieced together from various sources. For example, 53 percent of the U.S. population lives in counties with coastal areas, although such areas make up only 17 percent of the nation's contiguous land area (Crossett et al. 2004; U.S. Census Bureau 2005, 28).[1] Population density in coastal counties (exclud-

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[1] Coastal areas are defined by the U.S. National Oceanic and Atmospheric Administration as counties and equivalent areas with at least 15 percent of their land area either in a coastal watershed or in a coastal area between watersheds.

ing Alaska) is significantly higher than the national average—300 versus 98 persons per square mile—reflecting the limited land area involved (Crossett et al. 2004). This population swells in the summer months, as beaches are the top tourist destination (Douglass et al. 2005). Coastal areas are projected to experience continued development pressures as both retirement magnets and tourist destinations. For example, many of the most populous coastal counties located in California, south Florida, and Texas (Harris County), which already experience the effects of hurricanes and other tropical storms, are expected to grow rapidly in the coming decades (Crossett et al. 2004). This growth will generate demand for more transportation infrastructure and increase the difficulty of evacuation in an emergency.

Sea level rise, which climate scientists now believe to be virtually certain, in combination with expected population growth, will aggravate the situation, making housing and infrastructure in low-lying coastal areas even more vulnerable to extensive flooding and higher storm surges. An estimated 60,000 miles of coastal highways is already exposed to periodic coastal storm flooding and wave action (Douglass et al. 2005).[2] Those highways that currently serve as evacuation routes during hurricanes and other coastal storms could be compromised in the future. Although coastal highway mileage is a small fraction of the nearly 4 million miles of public roads in the United States, the vulnerability of these highways is concentrated in a few states, and some of these routes also serve as barriers to sea intrusion and as evacuation routes (Titus 2002).

Coastal areas are also major centers of economic activity. Six of the nation's top 10 U.S. freight gateways (by value of shipments) (BTS 2007) will be at risk from sea level rise (see Table 3-1). Seven of the 10 largest ports (by tons of traffic) (BTS 2007, 30) are located in the Gulf Coast, whose vulnerability was amply demonstrated during the 2005 tropical storm season.[3] The Gulf Coast is also home to the U.S. oil and gas industries, providing nearly 30 percent of the nation's crude oil production and

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[2] These estimates were made by using geographic information systems to measure the length of roads in coastal counties, superimposing data from the Flood Insurance Rate Maps of the Federal Emergency Management Agency to indicate those roads along the coast or tidal rivers likely to be inundated by storm surge in a 100-year storm, and finally adjusting the estimate to eliminate flooding from rainfall runoff.

[3] The Port of South Louisiana is the nation's largest port by tonnage and the largest agricultural export facility in the United States (Mineta 2005). Fortunately, it suffered only minor structural damage from Hurricane Katrina.

TABLE 3-1 **Top 10 U.S. Foreign Trade Freight Gateways by Value of Shipments, 2005**

Rank	Port	Mode	Shipment Value ($ billions)
1	John F. Kennedy International Airport, New York	Air	134.9
2	Los Angeles, California	Vessel	134.3
3	Detroit, Michigan	Land	130.5
4	New York, New York, and New Jersey	Vessel	130.4
5	Long Beach, California	Vessel	124.6
6	Laredo, Texas	Land	93.7
7	Houston, Texas	Vessel	86.1
8	Chicago, Illinois	Air	73.4
9	Los Angeles International Airport, California	Air	72.9
10	Buffalo–Niagara Falls, New York	Land	70.5

Source: BTS 2007, 39.

approximately 20 percent of its natural gas production (Felmy 2005). Several thousand off-shore drilling platforms, dozens of refineries, and thousands of miles of pipelines are vulnerable to disruption and damage from storm surge and high winds of tropical storms, as was recently demonstrated by Hurricanes Katrina and Rita. Those hurricanes halted all oil and gas production from the Gulf, disrupted nearly 20 percent of the nation's refinery capacity, and closed oil and gas pipelines (CBO 2006).[4] Climate scientists believe that global warming is likely to increase the intensity of strong hurricanes making landfall, increasing the risk of damage to or lengthening the disruption in the operation of these vital facilities.

Inland areas are also likely to experience the effects of climate change. Increased intense precipitation predicted by climate scientists for the continental United States could increase the severity of such events as the great flood of 1993. That event caused catastrophic flooding along 500 miles of the Mississippi and Missouri River system, paralyzing surface transportation systems, including rail, truck, and marine traffic. Major east–west traffic was halted for roughly 6 weeks in an area stretching from St. Louis

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[4] By the end of 2005—4 months after Hurricane Katrina and a little more than 3 months after Hurricane Rita—roughly one-quarter of crude oil production and one-fifth of natural gas production from the Gulf remained shut down (CBO 2006). Two percent of the nation's refinery capacity still was not operating.

west to Kansas City and north to Chicago, affecting one-quarter of all U.S. freight that either originated or terminated in the flood-affected region (Changnon 1996). Drier conditions are likely to prevail in the summer in midcontinental regions, such as the Saint Lawrence Seaway. Weather and vessel incidents cause most of the lock downtime on the seaway, but in 2000 and 2001, water levels were at their lowest point in 35 years, reducing vessel carrying capacity to about 90 percent of normal (BTS 2005, 140). If low water levels become more common because of dryer conditions due to climate change, freight movements in the region could be seriously impaired, and extensive dredging could be required to keep shipping channels open (Great Lakes Regional Assessment Team 2000; Quinn 2002). A longer shipping season afforded by a warmer climate, however, could offset some of the resulting adverse economic effects.

The vulnerability of transportation infrastructure to climate change is in part a function of its robustness and degree of protection from exposure to climate change effects (as is the case, for example, with seawalls and levees). It also depends on the amount of redundancy in the system. Box 3-1 illustrates how system redundancies proved critical to the rapid restoration of partial rail service during both Hurricane Katrina and the 1993 Mississippi River flood.[5] Yet the predominant trend has been for the railroads (as well as other owners of infrastructure) to shed uneconomical unused capacity by consolidating operations and abandoning underused lines. Likewise, major businesses, both manufacturing and retail, have reduced operating costs through just-in-time delivery strategies, but with the effect of increasing their vulnerability to disruptions or failures of the transportation system from either natural or human causes.

The network character of the transportation system can help mitigate the negative economic consequences of a shock to the system, particularly in the longer term, as shipments can be shifted to alternative modes or other regions can pick up the interrupted service. To illustrate, the Port of Gulfport, Mississippi, which was competing with New Orleans to be the second-largest container port in the Gulf, was 95 percent destroyed by the 30-foot storm surge from Hurricane Katrina (Plume 2005). Subsequently, much of the traffic shifted to other ports while Gulfport undertook major reconstruction of its facilities. On the other hand, the network character

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[5] See also the discussion later in this chapter of the results of a case study of Hurricanes Katrina and Rita commissioned for this study.

Box 3-1

Examples of the Role of System Redundancies in the Restoration of Critical Infrastructure Following Natural Disasters

Hurricane Katrina significantly damaged rail transport in the Gulf Coast region, particularly east–west traffic through the New Orleans interchange rail gateway—one of only four major rail crossings of the Mississippi River. CSX was the rail carrier most affected, sustaining significant damage to two-thirds of its track mileage between Mobile and New Orleans and to five railroad bridges between Biloxi and New Orleans (M. Hinsdale, presentation to the committee, Jan. 5, 2006). Estimated reconstruction costs were approximately $300 million, or about one-quarter of CSX's annual operating revenues available for capital investment. Nevertheless, CSX coped with the situation by using "borrowed" track of other, less hard-hit railroads in the region and by rerouting freight as far north as the St. Louis Mississippi River crossing. CSX has committed to rebuilding its coastal track in the short term but is evaluating less vulnerable alternative routes using existing rail corridors or constructing farther inland.

At the time, the flood of 1993 was hailed as the worst natural disaster ever experienced by the U.S. railroad industry. Total physical damages amounted to more than $282 million in 2005 dollars—23 percent of which included costs to operate detoured trains (Changnon 2006). In addition, because of the delays, the railroads lost revenues of $198 million. Nevertheless, nearly 3,000 long-distance trains were rerouted onto other railroad lines and some little-used lines bordering on abandonment. System redundancies and operating arrangements with other carriers enabled the affected railroads to continue operating—more slowly and at increased cost—but operating nonetheless.

of the transportation system can work to magnify the effects of a shock to the system, particularly when critical links are damaged or destroyed. This situation was well illustrated during Hurricane Katrina with the loss of critical highway and rail bridges.

POTENTIAL IMPACTS BY TRANSPORTATION MODE

The impacts of climate change on transportation infrastructure will differ depending on the particular mode of transportation, its geographic location, and its condition. This section is focused on those climate changes and weather parameters identified in the previous chapter (see Table 2-1) that climate scientists agree are most likely to occur over the course of this century and are of greatest relevance to transportation. Potential impacts on all modes of transport—land, marine, and aviation—are considered. However, the discussion is intended to be illustrative rather than comprehensive in coverage, highlighting major impacts, similarities and differences among modes, and implications for adaptation strategies.

Annex 3-1 gives the relevant climate and weather parameters along with potential impacts by transportation mode. In preparing this table, the committee drew on past efforts to identify transportation-sensitive weather conditions, as well as the collective expertise of the committee members. Some notable past reports include the *Weather Information for Surface Transportation National Needs Assessment Report* (OFCM 2002), the Metropolitan East Coast Assessment (Gornitz and Couch 2000; see detail in the next section), the U.S. Department of Transportation Workshop on Transportation and Climate Change (USDOT 2002), and an article by Black (1990). In addition, the discussion in this section draws heavily on a paper commissioned for this study (Peterson et al. 2006; see Appendix C) that provides a more detailed discussion of the potential impacts of climate change on transportation on the basis of recent global climate simulations.

The primary focus here is on the direct impacts of potential climate changes on transportation infrastructure. Nevertheless, many of these effects will be influenced by the environment in which the infrastructure is located. For example, increased precipitation levels in some regions will affect moisture levels in the soil and hydrostatic buildup behind retaining walls and abutments and the stability of pavement subgrades. Runoff from increased precipitation levels will also affect stream flow and sediment delivery in some locations, with potentially adverse effects on bridge foundations. Permafrost decline will affect Arctic land forms and hydrology, with potentially adverse effects on the stability of road- and rail beds. And sea level rise will affect coastal land forms, exposing many coastal areas to storm surge as barrier islands and other natural barriers disappear. Such changes are noted here, but their variability from region to region prohibits further elaboration.

There are also likely to be many indirect effects of potential climate changes on transportation. For example, possible climate-caused shifts in demographics or in the distribution of agricultural production, forests, and fisheries would have implications for road usage and other transport patterns between emerging economic centers and urban areas. Transportation patterns could also shift as the tourism industry responds to changes in ecologically or recreationally interesting destinations. Similarly, climate changes elsewhere in the world that shift markets or demographics could affect the U.S. transportation system.

Other indirect effects may be manifested at the interface between mitigation and adaptation. Likely U.S. regulation of greenhouse gas emissions by the Environmental Protection Agency will affect transportation activities, potentially shifting travel to more energy-efficient modes (see Appendix B). Furthermore, climate changes may present additional challenges to meeting air and water quality standards. For example, warmer summertime temperatures will exacerbate air pollution, particularly ground-level ozone, likely requiring further action to mitigate transportation-related emissions of pollutants. Similarly, changes in runoff resulting from modified precipitation regimes could affect water quality, with implications for roadway treatments.

Impacts of Warming Temperatures and Temperature Extremes

Land Transportation Modes

Land transportation modes comprise highways (including bridges and tunnels); rail (including private rail lines and public transportation); the vehicles that use these facilities—passenger cars, trucks, buses, rail and rail transit cars—and pipelines (recognizing that the latter are buried underground in many areas).

Projected warming temperatures and more heat extremes will affect all of these modes (see Annex 3-1). The effects of temperature warming are already being experienced in Alaska in the form of continued retreat of permafrost regions (see the discussion of Alaska below), creating land subsidence issues for some sections of the road and rail systems and for some of the elevated supports for aboveground sections of the Trans-Alaska pipeline. Warming winter temperatures have also shortened the season for ice roads that provide vital access to communities and industrial activities in remote areas.

Alaska's situation is quite different from that of many of the lower 48 states, however, where warming temperatures should have less dramatic, and in some cases beneficial, effects. In many northern states, for example, warming winter temperatures will bring about reductions in snow and ice removal costs, lessen adverse environmental impacts from the use of salt and chemicals on roads and bridges, extend the construction season, and improve the mobility and safety of passenger and freight travel through reduced winter hazards. Expected increases in temperature extremes, however, will have less positive impacts. More freeze–thaw conditions may occur, creating frost heaves and potholes on road and bridge surfaces and resulting in load restrictions on certain roads to minimize the damage. With the expected earlier onset of seasonal warming, the period of springtime load restrictions may be reduced in some areas but is likely to expand in others with shorter winters but longer thaw seasons.

Periods of excessive summer heat are likely to increase wildfires, threatening communities and infrastructure directly and bringing about road and rail closures in affected areas. Longer periods of extreme heat may compromise pavement integrity (e.g., softening asphalt and increasing rutting from traffic); cause deformation of rail lines and derailments or, at a minimum, speed restrictions (Rossetti 2002);[6] and cause thermal expansion of bridge joints, adversely affecting bridge operation and increasing maintenance costs. Pipelines in the lower 48 states are not likely to experience adverse effects from heat extremes.

Marine Transportation

Marine transportation infrastructure includes ports and harbors and supporting intermodal terminals and the ships and barges that use these facilities. Expected climate change impacts differ for coastal and inland waterways.

Warming winter temperatures, particularly in northern coastal areas, could be a boon for marine transportation. Fewer days below freezing would reduce problems with ice accumulation on vessels, decks, riggings, and docks; the occurrence of dangerous ice fog; and the likelihood of ice jams in ports. The striking thinning (Rothrock and Zhang 2005) and overall downward trend in the extent (Stroeve et al. 2005) of Arctic sea ice are regarded as a major opportunity for shippers (Annex 3-1). In the short

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[6] Proper installation of continuous welded rail usually prevents kinks from occurring, but not always (Changnon 2006).

term, continued reduction in Arctic sea ice should result in more ice-free ports, improved access to both ports and natural resources in remote areas, and longer shipping seasons. In the longer term, shippers are looking forward to new Arctic shipping routes that could provide significant cost savings in shipping times and distances (see the discussion of Alaska below). For the next several decades, however, warming temperatures and melting sea ice are likely to result in increased variability in year-to-year shipping conditions and higher costs due to requirements for stronger ships and support systems (e.g., ice-capable ship designs, icebreaker escorts, search and rescue support) (ACIA 2004). In addition, improved access to remote areas may increase the risk of environmental degradation to fragile ecosystems.

Warming temperatures are also likely to provide longer shipping seasons for the St. Lawrence Seaway and the Great Lakes (Annex 3-1). Because of the complex interaction among warmer temperatures, reduced lake ice, and increased evaporation, however, all nine climate model simulations suggest lower lake levels as the climate warms (Great Lakes Regional Assessment Team 2000).[7] With lower lake levels, ships will be unable to carry as much cargo, and hence shipping costs will increase, although some of the adverse economic impacts could be offset by a longer shipping season.[8] A recent study of the economic impact of climate change on Canadian commercial navigation on the Great Lakes, for example, found that predicted lowering of Great Lakes water levels would result in an estimated increase in shipping costs for Canadian commercial navigation of between 13 and 29 percent by 2050, all else remaining equal (Millard 2005).[9] Lower water levels could also create periodic problems for river traffic, reminiscent of the stranded barges on the Mississippi River during the drought of 1988 (du Vair et al. 2002). In the longer run, of course, less

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[7] See in particular Chapter 4 on climate change and shipping/boating.

[8] According to the Lake Carriers' Association, a 1,000-foot-long vessel typically used for intralake transport loses 270 tons of capacity for each inch of draft loss. (Draft is the distance between the water line and the bottom of the vessel.) Oceangoing vessels, sized for passage through the St. Lawrence Seaway, are approximately 740 feet long and lose 100 tons of capacity for each inch of draft lost (Great Lakes Regional Assessment Team 2000).

[9] Impacts were estimated on the basis of three climate scenarios: one that assumes a doubling of the atmospheric concentration of CO_2 by midcentury and two that assume a more gradual increase in greenhouse gases and include the cooling effects of sulfate aerosols. The study found that economic impacts varied widely by commodity and route.

efficient waterborne commodity movement would likely result in shifts to other transportation modes, such as truck and rail. Increased dredging could offset some of the impacts of climate change, but at a high cost and with potentially negative environmental consequences.

Air Transportation

Air transportation comprises airports and ground facilities, as well as the airplanes that carry both passengers and freight and the air traffic control system.

Warming temperatures and possible increases in temperature extremes will affect airport ground facilities—runways in particular—in much the same way that they will affect roads. In Alaska, where use of air transport is atypically high relative to land transportation modes and many airstrips are built on permafrost, continued retreat and thawing of permafrost could undermine runway foundations, necessitating major repairs or even relocation of some landing strips (Annex 3-1; U.S. Arctic Research Commission Permafrost Task Force 2003). In contrast, airports in many of the lower 48 northern states are likely to benefit from reductions in the cost of snow and ice removal and in the environmental impacts of salt and chemical use. Airlines could benefit as well from reduced need for deicing of airplanes. The amount of any reduction, however, will depend on the balance between expected warming and increased precipitation.

More heat extremes, however, are likely to be problematic. They could cause heat buckling of runways. Extreme heat can also affect aircraft lift; hotter air is less dense, reducing mass flowing over the wing to create lift. The problem is exacerbated at high-altitude airports. If runways are not sufficiently long for large aircraft to build up enough speed to generate lift, aircraft weight must be reduced or some flights canceled altogether. Thus, increases in extreme heat are likely to result in payload restrictions, flight cancellations, and service disruptions at affected airports, and could require some airports to extend runway lengths, if feasible. An analysis by the National Oceanic and Atmospheric Administration for the Denver and Phoenix airports estimated summer cargo loss (June through August) for a single Boeing 747 of about 17 and 9 percent, respectively, by 2030 because of the effects of increased temperature and water vapor (T. R. Karl and D. M. Anderson, Emerging Issues in Abrupt Climate Change, briefing, March 12, 2007).

Impacts of Increased Heavy Precipitation and Sea Level Rise

Land Transportation Modes

The frequency, intensity, and duration of intense precipitation events are important factors in design specifications for transportation infrastructure. Probabilistic estimates of rainfall intensities for a range of durations (5 minutes to 24 hours) for return periods, or recurrence intervals, of 20, 50, and 100 years have been used by civil engineers for designs of road culverts, storm water drainage systems, and road- and rail beds. Projected increases in intense precipitation events will necessitate updating design specifications to provide for greater capacity and shorter recurrence intervals, increasing system costs.

The most immediate impact of more intense precipitation will be increased flooding of coastal roads and rail lines (Annex 3-1). Expected sea level rise will aggravate the flooding because storm surges will build on a higher base, reaching farther inland (Titus 2002). In fact, the chapter in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report on North America identifies coastal flooding from expected sea level rise and storm surge, especially along the Gulf and Atlantic coasts, as one of the most serious effects of climate change (Burkett 2002 in Field et al. 2007). Indeed, several studies of sea level rise project that transportation infrastructure in some coastal areas along the Gulf of Mexico and the Atlantic will be permanently inundated sometime in the next century (Dingerson 2005; Gornitz and Couch 2000; Leatherman et al 2000; Titus 2002). Low-lying bridge and tunnel entrances for roads, rail, and rail transit will also be more susceptible to flooding, and thousands of culverts could be undersized for flows. Engineers must be prepared to deal with the resulting erosion and subsidence of road bases and rail beds, as well as erosion and scouring of bridge supports.[10] Interruption of road and rail traffic is likely to become more common with more frequent flooding.

The impact of sea level rise is limited to coastal areas, but the effect of intense precipitation on land transportation infrastructure and operations is not. For example, a record-breaking 24-hour rainstorm in July

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[10] Scour is the hole left behind when sediment (sand and rocks) is washed away from the bottom of a river. Although scour may occur at any time, scour action is especially strong during floods. Swiftly flowing water has more energy than calm water to lift and carry sediment downriver. Removal of sediment from around bridge piers or abutments (piers are the pillars supporting a bridge and abutments the supports at each end of a bridge) can weaken and ultimately undermine the integrity of bridges (Warren 1993).

1996 resulted in flash flooding in Chicago and its suburbs, with major impacts on the urban area. Extensive travel delays occurred on metropolitan highways and railroads, and streets and bridges were damaged. Commuters were unable to reach Chicago for up to 3 days, and more than 300 freight trains were delayed or rerouted (Changnon 1999).

Pipelines may also be affected by increased intense precipitation. For example, federal regulations require that pipelines carrying hazardous materials in the lower 48 states be buried with a minimum of 3 feet of cover—up to 5 feet near heavily populated areas. Intense precipitation can erode soil cover and cause subsidence (i.e., sinking of the earth underneath the pipeline). Scour and shifting of pipelines are a major problem in shallow riverbeds, where pipelines are more exposed to the elements (B. Cooper, Association of Oil Pipe Lines, personal communication, Dec. 7, 2006). Ultrashallow seabed waters can also be a problem if the pipeline becomes exposed and subject to potential movement and even fracture from continuing storm wave action.

Changes in seasonal precipitation levels, with more precipitation falling as rain than snow, can be beneficial but can also create problems in certain areas. For example, California's transportation infrastructure could be sensitive to even modest changes from frozen to liquid precipitation. When precipitation falls as rain rather than snow, it leads to immediate runoff and increases the risk of floods, landslides, slope failures, and consequent damage to roadways, especially rural roadways in the winter and spring months (du Vair et al. 2002). Navigable rivers with both rainfall and snowmelt responses would probably see greater winter volume flows associated with a greater risk of flooding (U.S. Global Change Research Program 1999).

Marine Transportation

Coastal ports and harbor facilities will be affected by increased intense precipitation and sea level rise. Landside facilities will be particularly vulnerable to flooding from an increase in intense precipitation events and to the impacts of higher tides and storm surges from rising seas (Annex 3-1). Sea level with respect to dock level is an important consideration at both wet and dry docks, general cargo docks, and container berths for clearance of dock cranes and other structures. Changes due to increased intense precipitation and sea level rise could require some retrofitting of facilities. At a minimum, they are likely to result in increased weather-related delays and periodic interruption of shipping services.

The navigability of shipping channels is also likely to change. Some channels may be more accessible to shipping farther inland because of sea level rise. The navigability of others, however, could be adversely affected by changes in sedimentation rates and the location of shoals. In other areas, a combination of sea level rise and storm surge could eliminate waterway systems entirely. For example, the Gulf Coast portion of the intercoastal waterway will likely disappear with continued land subsidence and the disappearance of barrier islands. This will bring an end to coastal barge traffic, which helps offset rail and highway congestion; all ships will have to navigate the open seas. According to the U.S. Geological Survey, Hurricanes Katrina and Rita alone destroyed 217 square miles of coastal wetlands. This loss represents slightly more than two-fifths of that which scientists had previously predicted would take place over the 50-year period from 2000 to 2050 (Barras 2006).

The increased intense precipitation and periodic droughts predicted for the midcontinental United States will affect shipping on the Mississippi and Missouri River system. Increased precipitation could bring a repetition of the floods that devastated travel on the Upper Mississippi River in 1993. Droughts have a greater influence on commercial navigation on the lower portion of the river—from St. Louis to the Gulf—where there are no locks and dams and channel depths are entirely dependent on river flows. The 1988 drought, for example, stranded more than 4,000 barges, shifting freight to the railroads, which experienced increased business in hauling grains and other bulk commodities (Changnon 2006; du Vair et al. 2002). In a recent study of climate change impacts on the lock and dam system on the Middle Mississippi, between the Missouri and Ohio Rivers, the U.S. Army Corps of Engineers concluded that the uncertainty associated with predicting future river flows called for a "wait and see," monitoring approach rather than for expensive infrastructure improvements (Institute for Water Resources 2005). Nevertheless, feasibility studies for navigation projects have a 50-year planning horizon, thus requiring at least some consideration of the impacts of climate change and identification of the most robust strategies under a range of different possible scenarios.

Air Transportation

Several of the nation's largest airports lie in coastal zones, built along tidal waters, sometimes on fill (Titus 2002). Their runways are particularly vulnerable to flooding and erosion from increased intense precipitation and, in the longer term, from sea level rise. Some airports, such as New York's LaGuardia, are protected by dikes (see the discussion below of the Metropolitan East Coast Assessment), but others may require protection. At a minimum, increased intense precipitation is likely to cause increased disruptions and delays in air service and periodic airport closures.

Impacts of More Intense Tropical Storms

Climate scientists believe that more intense tropical storms are a likely effect of climate change. Three aspects of tropical storms are relevant to transportation: precipitation, winds, and wind-induced storm surge. All three tend to be much greater during strong storms. Such storms tend to have longer periods of intense precipitation; wind damage increases with wind speed; and wind-induced storm surge and wave action can have devastating effects.

All modes of infrastructure are affected by more intense tropical storms. Sustained storm surge and damaging wave action displaced highway and rail bridge decks during the recent hurricanes along the Gulf Coast, not to mention the loss of thousands of sign and signal supports. Shipping was disrupted, and barges that were unable to get out of harm's way in time were destroyed. Airports were closed and sustained wind damage. Refineries were damaged, and barge traffic between offshore drill sites and coastal pumping facilities was suspended. The vulnerability of different transportation modes, as well as their resilience to intense tropical storms, is well documented by the case study of the transportation sector's response to and recovery from Hurricanes Katrina and Rita discussed later in this chapter.

REVIEW OF ASSESSMENTS FOR PARTICULAR AREAS OR REGIONS

Few studies have attempted to examine the potential impacts of climate change on transportation in a particular area or region. Those the committee found are briefly reviewed in this section.

The Metropolitan East Coast Assessment

This study of the impacts of climate change in the tristate area of New York, New Jersey, and Connecticut focused on transportation infrastructure because of the enormous value of the Metropolitan East Coast's (MEC's) highly developed infrastructure to the region's nearly $1 trillion economy (Jacob et al. 2007).[11] With more than 2,000 km of shoreline and extensive areas of vulnerable residential development and business centers and supporting infrastructure, the focus was on the effects of sea level rise.

The study used two global climate models, tailored to the MEC area, to describe possible future climate scenarios over the 21st century.[12] The projections showed a potential rise in sea level of 0.24 to 1.08 m (nearly 0.8 to 3.5 ft) between the reference year, 1980, and 2080. More important, the combined effect of sea level rise and storm surge could result in flood heights for the 100-year coastal storm of 3.2 to 4.2 m (10.5 to nearly 14 ft) above the current reference height of 2.96 m (nearly 10 ft) for New York City. Thus, projected increases in sea level could raise the frequency of coastal storm surges and related flooding by a factor of 3, on average. Moreover, the return interval of the 100-year storm could shorten to as little as 4 to 60 years, depending on the climate scenario.

Elevation maps of areas within the 3-m (10-ft) reference height above current sea level reveal that roughly 10 percent of the total MEC land area—portions of lower Manhattan; coastal areas of Brooklyn, Queens, Staten Island, and Nassau County; and the New Jersey Meadowlands—could experience a marked increase in flooding frequency (see Figure 3-1). Many critical transportation infrastructure facilities lie at elevations 2 to 6 m (6 to 20 ft) above present sea level—well within the range of current and projected coastal storm surges of hurricanes and more frequent nor'easters (see Figure 3-2). Most area rail and tunnel entrance points, for example, as well as three major airports, lie at elevations of 3 m or less.[13]

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[11] The study, one of 18 regional components of the *U.S. National Assessment of the Potential Consequences of Climate Variability and Change* organized by the U.S. Global Change Research program under the Clinton administration, was one of the only assessments that examined transportation infrastructure.

[12] The two models used were the United Kingdom Hadley Centre model and the model from the Canadian Centre for Climate Modeling and Analysis. For a more detailed discussion, see Jacob et al. 2000.

[13] Some of these facilities are protected but may need modification. For example, the Port Authority of New York and New Jersey (PANYNJ), an active participant in the MEC study, built a dike and levee system to protect LaGuardia Airport. After the severe nor'easter in 1992, PANYNJ built floodgates to protect the Port Authority Trans-Hudson tunnel under the Hudson River, which had flooded and put commuter trains out of operation for 10 days (Jacob et al. 2007).

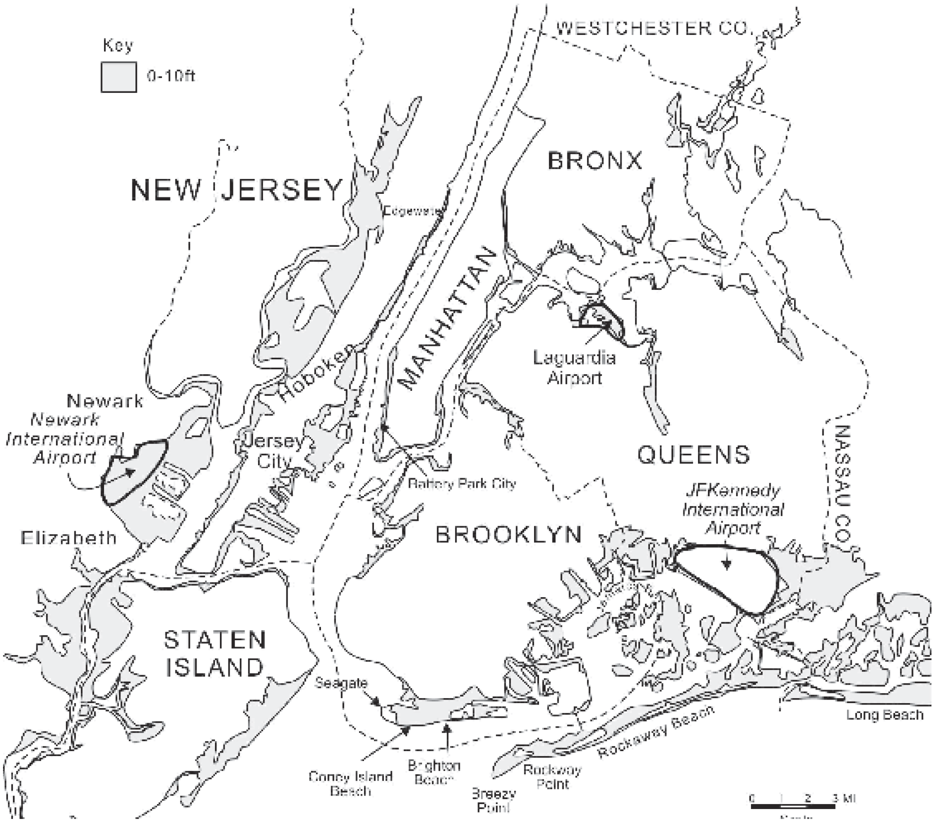

FIGURE 3-1 **Central portion of the MEC study area.** Gray shading shows the areas at elevations below 3 m (10 ft) above present mean sea level. [*Source:* Jacob et al. 2007. (Copyright Elsevier 2007. Reprinted with permission of Elsevier Limited, Oxford, United Kingdom.)]

The New York metropolitan area is no stranger to the devastating impacts of flooding. For example, the nor'easter of December 1992 produced some of the worst flooding in the area in 40 years, resulting in an almost complete shutdown of the regional transportation system and evacuation of many seaside communities (Jacob et al. 2007). More recently, heavy rainstorms in September 2004 and in August 2007 crippled the New York City transit system. Torrential rainfall (nearly 3 inches of rain in a 1-hour period in the 2007 event) overwhelmed the drainage system, designed to handle only about half that amount of rainfall, sending water into the subway tunnels (Chan 2007). Recent emergency planning for

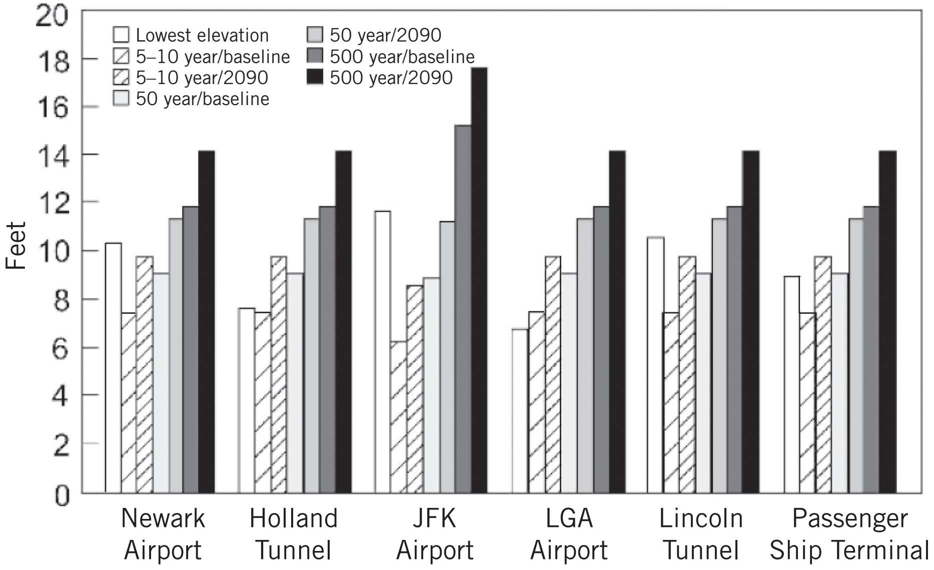

FIGURE 3-2 **Current lowest critical elevations of facilities operated by the Port Authority of New York and New Jersey compared with changing storm elevations at these locations for surge recurrence periods of 10, 50, and 500 years between 2000 (baseline) and the 2090s.** Note that 10 ft equals approximately 3 m. [*Source:* Jacob et al. 2007. (Copyright Elsevier 2007. Reprinted with permission of Elsevier Limited, Oxford, United Kingdom.)]

New York has focused on a worst-case scenario evacuation of approximately 2.3 million New Yorkers, many by transit, in the event of a Category 3+ hurricane.

Flooding and storm surge will only be exacerbated by sea level rise. The New York metropolitan area is constantly rehabilitating and modernizing its aging capital stock, providing opportunities to build in new protections against potential increased flooding. The MEC study proposes several measures, including incorporating sea level rise into the design, siting, and construction of new infrastructure facilities or renovation of existing facilities; recognizing sea level rise in federal Flood Insurance Rate Maps used by many local jurisdictions for land use planning and construction regulations; instituting land use measures to prevent new or further development in highly vulnerable coastal areas; and constructing strategically placed storm surge barriers, similar to those in operation in the Netherlands and across the Thames River near London, to protect highly vulnerable and valuable areas.

Climate's Long-Term Impacts on Metro Boston Study

The Environmental Protection Agency funded a 3-year project to study the potential impacts of climate change on infrastructure systems, including transportation, in the metropolitan Boston area and to recommend strategies for preventing, reducing, or managing the risk (Kirshen n.d.). The long-term economic success and quality of life of the region depend heavily on reliable infrastructure systems, which could be adversely affected by climate change. The concern is that global warming may result in sea level rise and increased flooding, higher peak summer temperatures, and more frequent and intense winter and summer storms with higher storm surges. At the same time, continued population and economic growth will result in increased development pressure on already vulnerable coastal and riverine areas, increasing not only the amount of infrastructure at risk but also the amount of runoff that must be handled by area rivers, streams, and storm water systems (Suarez et al. 2005).

The human and economic costs of disruption to infrastructure systems from flooding and storm surge in the area were dramatically illustrated by the devastating storm of October 1996. Drainage systems were inadequate to handle the 100-year storm. Backups and overflows affected several sections of the city, causing $70 million in property damage in addition to disrupting business and personal travel (Kirshen et al. 2004, 71). Portions of the Boston Museum of Fine Arts and Northeastern University were flooded, as were a Green Line tunnel and four rapid transit stations, causing major damage and interrupted service for several weeks.

The study analyzed climate change impacts on seven sectors, including transportation.[14] The impact analysis for land transportation systems focused on flooding and impacts on the road system, emphasizing the effect on system performance rather than on infrastructure damage (Suarez et al. 2005). The methodology involved integrating projected changes in land use, demographics, economic activity, and climatic condi-

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[14] The sectors were energy use, sea level rise, river flooding, water supply, public health (heat-stress mortality), localized systems (water quality, tall buildings, bridge scour), and transportation.

tions into the urban transportation modeling system of the Boston Metropolitan Area Planning Council (MAPC).[15] The model was then used to simulate traffic flows for a range of different flooding scenarios for a base case year (2003) and a future year (2025), incorporating anticipated socioeconomic changes, as well as projected new links or increased capacity in the road network.[16] Finally, the models were rerun to take into account the aggregate effect of increased flooding on delays and lost trips over the period 2000 to 2100.[17]

The results show that delays and trips lost between the baseline year 2000 and 2100 would increase by 80 and 82 percent, respectively, as a result of increased flooding attributable to climate change (Suarez et al. 2005, 240). Nevertheless, because of the large number of daily baseline trips in the Boston metropolitan area—approximately 14.6 million in 2000—these percentage increases represent relatively modest effects. The results also reflect the redundancy of the transportation network that is typical of a mature metropolitan area, which lessens but does not eliminate vulnerability. For example, although coastal areas are more densely populated, the road network is less redundant, so that residents are unable to make trips when the roads become inundated. In contrast, riverine floods result in increased vehicle miles and vehicle hours traveled. Travelers have more alternative routes available, but many are major commuter routes, thereby increasing congestion and time traveled (Suarez et al. 2005).

The report concludes that even if one uses high monetized values for lost trips and incremental delays, the impacts are "significant, but probably not large enough to justify a major effort for adapting the physical

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[15] MAPC forecasts population and employment growth to 2025 at the town level, providing the best available estimates of the spatial evolution of people and economic growth in the region. The study assumed that similar growth trends would persist up to 2050 and then remain constant. The Canadian Climate Centre and Hadley Centre climate scenarios used in the New England Regional Assessment—another regional component of the *U.S. National Assessment*—were superimposed over time series data on local weather conditions to provide the climate change predictions for 2001 to 2100 (Kirshen et al. 2004).

[16] Twelve flooding scenarios were developed to reflect different years of simulation, areas flooded (none, 100-year, and 500-year floodplains), and type of flooding (coastal, riverine, or both). Flood Insurance Rate Maps were used to identify coastal and riverine floodplains, and these were overlaid on maps showing land use and the road networks within the boundary of each traffic analysis zone used in the model (Kirshen et al. 2004).

[17] Two climate states were modeled—one assuming no climate change, projecting past trends into the future by bootstrapping from 50 years of rainfall and sea level data for the Boston area, and the second assuming climate changes in line with available climate model predictions. The difference in network performance between the two scenarios was attributed to climate change (Kirshen et al. 2004).

infrastructure to expected climatic conditions, except for some key links" (Suarez et al. 2005, 231). The study, however, did not take into consideration the potential physical damage to transportation infrastructure and repair costs due to climate change that also must be part of any investment decision.

Seattle Audit of Climate Change Impacts

Since the early 1990s, Seattle has been a leader in its efforts to reduce greenhouse gas emissions that contribute to climate change (Soo Hoo and Sumitani 2005). Because the impacts of climate change are likely to persist well into the 21st century, however, policy makers have also recognized the need to develop appropriate adaptation strategies. Seattle's Office of City Auditor initiated a series of reviews of how changes in the climate of the Pacific Northwest region would affect the operations and infrastructure of various city departments. The first review was focused on the Seattle Department of Transportation (SDOT), which is responsible for the city's $8 billion transportation infrastructure, including its roadways, most bridges, and bike paths (Soo Hoo and Simitani 2005).

The primary changes predicted by climate scientists for the Pacific Northwest in the 21st century are warmer temperatures, rising sea levels, and increased winter precipitation. The study identified five potential types of impact.

First, increased winter precipitation could lead to more flooding and landslides, which could damage the city's transportation infrastructure and underlying utilities and hamper the mobility and safety of travel.[18] More flooding, for example, could overwhelm the existing storm water drainage system, causing soil saturation and surface erosion. It could also exacerbate erosion of soil around roads, bridge footings, and retaining walls.

Second, rising sea levels could affect the adequacy of seawall heights and bridge clearances. SDOT had considered sea level rise in developing design standards for a major Alaskan Way Seawall replacement project, but questions were raised regarding whether the projected sea level rise was underestimated.

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[18] Seattle Public Utilities has primary responsibility for responding to emergencies, such as landslides and surface flooding. However, SDOT is primarily responsible when the structural integrity of public streets, bridges, and retaining walls is threatened (Soo Hoo and Sumitani 2005).

Third, increased precipitation and temperatures and sea level rise would adversely affect bridge operations. More than one-third of Seattle's 105 bridges are currently rated as being in poor condition.[19] Warmer temperatures could cause greater thermal expansion at bridge expansion joints, affecting bridge operations and adding to maintenance costs. Increased winter precipitation could exacerbate erosion around bridge footings, and rising sea levels could affect bridge clearances (see Figure 3-3).

Fourth, warmer temperatures and increased precipitation could cause roadways to deteriorate. SDOT is responsible for approximately 1,500 lane miles of arterial streets and 2,700 lane miles of nonarterial streets. The city's arterial streets are in good condition, but there is a backlog of repair and resurfacing projects. Climate changes could shorten street lives (Figure 3-3). Hotter summers could result in pavement softening and buckling and the appearance of heat bumps, although use of warmer-temperature asphalt mix could mitigate some of these effects. Increased precipitation would increase street flooding and tax drainage systems.

Finally, warmer and longer summers and reduced summer precipitation would place stress on trees and landscaped areas in the city's rights-of-way, requiring increased maintenance.[20] SDOT's Urban Forestry unit is already considering the use of drought-resistant plants and other strategies to offset the negative effects of climate change.

In response to the report, SDOT noted that it is including climate change as a factor in the scoping of new projects. It is also undertaking a new asset management effort that will focus on replacement cycles for all transportation infrastructure; climate change impacts will be considered as one factor in determining the adequacy of proposed replacement and rehabilitation projects (E. Paschke, SDOT, personal communication, April 14, 2006). That being said, SDOT noted that the long time frames and uncertainties of expected climate changes, coupled with maintenance backlogs and short-term planning horizons for operating budgets, justify "a prudent approach: one that combines watchfulness in following trends in climate

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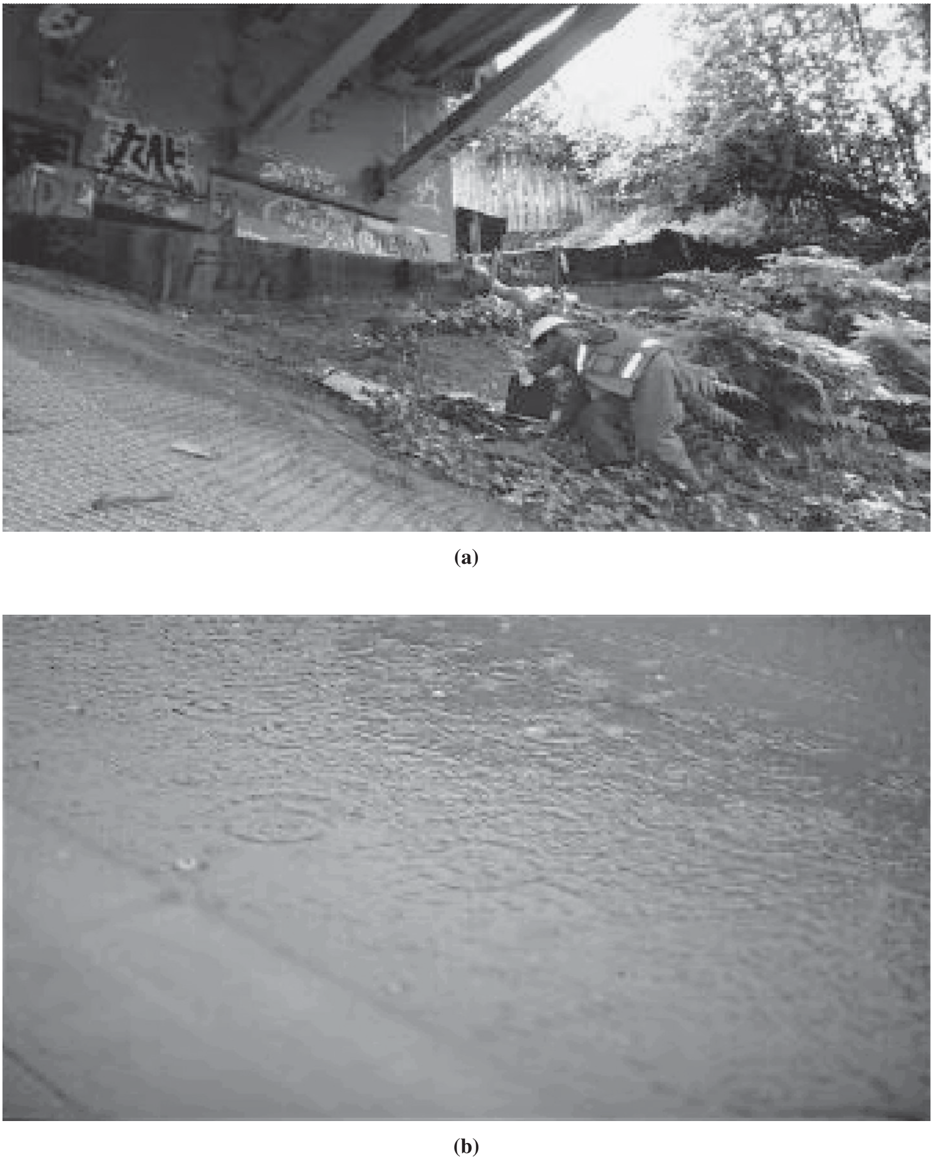
[19] According to the 2004 *Report of the Citizens' Transportation Advisory Committee,* 37 percent of the city's bridges are in "poor condition or worse," and 4 percent already face weight restrictions because of critical deficiencies (Soo Hoo and Sumitani 2005, 20).

[20] SDOT's Urban Forestry unit maintains an inventory of 130 acres of land in city rights-of-way. Approximately 30,000 trees are located on city-owned land, with an estimated value of $100 million. Approximately half of the city's landscaped areas are currently rated as being in good condition (Soo Hoo and Sumitani 2005, 24).



(a)

(b)

FIGURE 3-3 **Potential impacts of climate change on Seattle's transportation infrastructure.** (*a*) SDOT already monitors some bridges, such as the Admiral Way Bridge, because of erosion concerns. (Photo courtesy of SDOT.) (*b*) Increased rainfall could cause more rapid deterioration of pavements in city streets. (Photo courtesy of Seattle Municipal Archives.) (*Source:* Soo Hoo and Sumitani 2005.)

change, including anticipating how climate change may increase our resource needs, while we continue with our efforts to mitigate the causes" (Soo Hoo and Sumitani 2005, 46). Finally, SDOT officials recommended an interdepartmental team to coordinate a comprehensive assessment of projections for sea level rise, as well as data on other issues related to climate change, that could be used to revise existing or establish new and consistent standards reflecting climate change across all city infrastructure investment projects (Soo Hoo and Sumitani 2005).

Alaska

Alaska is already experiencing some of the effects of climate change, such as warming temperatures and continued shrinkage of permafrost regions—areas of permanently frozen ground below the surface layer—with consequences for all modes of land transportation.[21] Warming temperatures are also affecting marine transportation. Decreased concentrations and extent of sea ice in the Arctic Ocean have lengthened the ice-free shipping season, expanded shipping along the Northern Sea Route, and opened the possibility of a Northwest Passage for shipping.[22] At the same time, however, more open seas have exposed coastal villages along northern and western Alaska to increased storms and wave action, with attendant erosion. Coastal villages, along with their infrastructure, will need greater protection or may have to be relocated (G. Wendler, Geophysical Institute Climate Center, personal communication, March 2, 2006).

As noted earlier, Alaska's transportation infrastructure differs from that of the lower 48 states. Although Alaska is twice the size of Texas, both its population and road mileage are more like Vermont's. Of its 12,700

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[21] Permafrost refers to soil, rock, or sediment that has remained below 32°F for 2 or more consecutive years (ACIA 2004). The 2-year designation is intended to exclude the overlying ground surface layer that freezes each winter and thaws each summer. Regions are classified into continuous permafrost zones, in which the permafrost occupies the entire area, and sporadic or discontinuous permafrost zones, in which the permafrost underlies from 10 to 90 percent of the land and may be only a few meters thick in places. Permafrost is further classified into two types: (*a*) cold permafrost, where temperatures remain below at least 30°F, and the introduction of considerable heat can be tolerated without thawing; and (*b*) warm permafrost, where temperatures remain just below freezing, and very little additional heat may induce thawing.

[22] The Northern Sea Route encompasses all routes across the Russian Arctic coastal seas to the Bering Strait. The Northwest Passage is the name given to the marine routes between the Atlantic and Pacific Oceans along the northern coast of North America that span the straits and the sounds of the Canadian Arctic Archipelago.

miles of roads, for example, only about 30 percent are paved (U.S. Arctic Research Commission Permafrost Task Force 2003, 28). The road and rail networks are concentrated largely in the south-central part of the state, near major population centers. Transport by air is much more common than in most states. Alaska has 84 commercial airports and more than 3,000 airstrips, many of which serve as the only means of transport for rural communities. The state also is home to the Trans-Alaska Pipeline System (TAPS).

Two recent studies (ACIA 2004; U.S. Arctic Research Commission Permafrost Task Force 2003) considered the impacts of a warming Arctic on both Alaska and its infrastructure, particularly the effects on permafrost. The band of discontinuous, warm permafrost has been moving northward for some years. For highways, thawing of the permafrost causes settling of the roadbed and frost heaves that adversely affect roadway performance, such as load-carrying capacity. The majority of the state's highways are located in areas where permafrost is discontinuous, and dealing with thaw settlement problems already claims a significant portion of highway maintenance dollars [M. Miles, Alaska Department of Transportation and Public Facilities (DOT&PF), personal communication, March 3, 2006]. Nevertheless, a road rehabilitation cycle of about 15 years is sufficiently short to enable engineers to adapt to changing climate conditions. Thus, they are able to anticipate some problems created by thawing prior to construction and have developed a number of mitigation techniques.[23] In addition, the Cold Regions Research and Engineering Laboratory (CRREL),[24] in partnership with DOT&PF and the University of Alaska, has developed a web-based geographic information system tool—the Alaska Engineering Design Information System (AEDIS)—for use in monitoring and design. AEDIS provides geographic-specific data on climate factors, such as precipitation levels, permafrost, and snow depth, that can be used to derive engineering design parameters (e.g., load-bearing capacity), schedule maintenance, and select optimum transportation routes (T. Douglas, CRREL, personal communication, March 9, 2006).

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[23] For example, insulation can be placed in the road prism (area of road containing the road surface, cut slope and fill slope), and different types of passive refrigeration schemes can be used, including thermosiphons, rock galleries, and "cold culverts" (M. Miles, Alaska DOT&PF personal communication, March 3, 2006).

[24] The Civil and Infrastructure Engineering Branch of CRREL, part of the U.S. Army Corps of Engineers, conducts applied research and develops innovative engineering solutions for facilities and infrastructure that operate under freezing, thawing, and extreme temperature differences.

Less flexible and longer-lived bridges and large culverts are sensitive to movement caused by thawing permafrost and are more difficult than roads to repair and modify for changing site conditions. Thus, designing these facilities to take climate change into account is more critical than is the case for roads (O. Smith, University of Alaska, Anchorage, personal communication, March 1, 2006). Another impact of climate change on bridges is increased scour. Hotter, dryer summers have led to increased glacial melting and longer periods of high streamflows, leading to both increased sediment transport on rivers and scour at bridge crossings. A network of sonars has been installed on several scour-critical bridges around the state, and the monitoring data are regularly sent to Alaska DOT&PF (J. Conaway, United States Geological Survey, personal communication, March 8, 2006).

Temporary ice roads and bridges are commonly used in many parts of Alaska to access northern communities and provide support for the mining and oil and gas industries. Rising temperatures have already shortened the season during which these critical facilities can be used (ACIA 2004).

Like the highway system, the Alaska Railroad crosses permafrost terrain, but the railroad does not extend northward into the zone of continuous permafrost. While frost heave and settlement from thawing affect some portions of the track, increasing maintenance costs, major relocations of existing track will not likely be required (U.S. Arctic Research Commission Permafrost Task Force 2003).

Alaska's airports and airstrips are located throughout the state. A significant number of airstrips in the southwest, the northwest, and the interior are built on permafrost and thus will require major repairs or relocation if their foundations are compromised by thawing (U.S. Arctic Research Commission Permafrost Task Force 2003).

TAPS, which stretches from Prudhoe Bay in northern Alaska to the ice-free port of Valdez in the south, crosses a wide range of permafrost types and varying temperature conditions. More than half of the 800-mile pipeline is elevated on vertical supports over thaw-unstable permafrost to avoid problems of permafrost degradation, soil liquefaction, and land subsidence (U.S. Arctic Research Commission Permafrost Task Force 2003). Because the system was designed in the early 1970s on the basis of permafrost and climate conditions of the 1950–1970 period, it requires continuous monitoring, and some supporting members have had to be replaced. The Federal–State Joint Pipeline Office, which regulates TAPS, and the Alyeska Pipeline Company, which operates it, do not regard permafrost degradation as a problem, but this assessment does not take into account the Arctic Climate Impact Assessment predictions for the next 30 years (U.S. Arctic Research Commission Permafrost Task Force 2003).

Arctic marine transport will benefit from climate changes. Observations over the past 50 years show a decline in the extent of Arctic sea ice in all seasons, with the most prominent retreat in the summer (ACIA 2004). Climate models project an acceleration of this trend, opening new shipping routes and extending shipping seasons along Arctic coastlines, including Alaska. Improved accessibility, however, will not be uniformly distributed. For example, the navigation season[25] for the Northern Sea Route is projected to increase from 20 to 30 days per year to about 90 to 100 days by 2080 (ACIA 2004, 83). For trans-Arctic voyages, this route represents up to a 40 percent savings in distance from northern Europe to northeastern Asia and the northwest coast of North American compared with southerly routes via the Suez or Panama Canal. In contrast, reduction in the extent of sea ice may create highly variable conditions in the Northwest Passage, reflecting the complex geography of the Canadian Arctic that could not be captured by the regional climate models used for the Arctic Climate Impact Assessment.

In sum, recent climate change assessments show that Alaska is already experiencing the effects of climate change, particularly warming of the Arctic climate and thawing of permafrost. The effects are projected to accelerate during this century (ACIA 2004), and Alaska's experience with adaptation may be instructive for some other cold-weather regions of the United States. Most of the state's transportation infrastructure was designed for permafrost, and those systems with relatively short rehabilitation cycles relative to projected climate changes will have time to adapt to the changes. Nevertheless, projected changes are likely to require at best increased monitoring of climate conditions and higher maintenance costs, and at worst more major retrofits or even relocation of some facilities. According to one transportation professional, the greatest challenge lies not in dealing with the impacts of climate change but in not knowing exactly what changes to expect or when (B. Connor, Alaska University Transportation Center, personal communication, March 9, 2006).

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[25] The navigation season is generally defined as the number of days per year when there is less than 50 percent sea-ice concentration.

Gulf Coast

The committee commissioned a special case study of the transportation sector's response to and recovery from Hurricanes Katrina and Rita.[26] One of the primary objectives of this study was to examine the vulnerability of the transportation system to a major disruption, with a particular focus on the impact of an interruption on national-level movement of freight.

The Gulf Coast is one of the key economic and population centers of the United States, home to more than 15 million Americans located in five states (Texas, Louisiana, Mississippi, Alabama, and Florida) and three major metropolitan areas. The low-lying flat land along the Gulf Coast, skirting the subtropical waters of the Gulf of Mexico, makes the region vulnerable to major hurricanes, more so than any other region in the United States. However, the geography that makes the coastal area dangerous during hurricanes also makes it attractive for industrial and commercial development. Several of the nation's most heavily used ports are located along the Gulf Coast. The Ports of South Louisiana and Houston—among the world's 10 most heavily used ports—are particularly attractive to international shippers because of the area's centralized location with respect to the rest of the nation and its wealth of transportation connections by pipeline, highway, rail, and river. The Gulf of Mexico also contains some of the largest U.S. oilfields and, with its large share of domestic natural gas and petroleum production, combined with its status as a major energy importer, is the epicenter of the U.S. petrochemical industry.

Hurricane Katrina was the most destructive and costliest natural disaster in U.S. history, claiming more than 1,800 lives and causing an estimated $75 billion in damage. Hurricane Rita, exceeding Katrina in both intensity and maximum wind speed, claimed 120 lives and caused approximately $10 billion in damage. The significantly lower casualty and damage levels of Rita can be attributed to its easterly track, which spared the Houston metropolitan area from the worst of the storm. The unusually large losses of life and physical destruction of Hurricane Katrina resulted from a levee failure and the inability of the floodwaters to recede because so much of New Orleans lies below sea level. A failed evacuation plan for the car-less exacerbated the human toll. Both storms seriously disrupted transportation systems. Key highway and railroad bridges were heavily damaged or

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[26] This section draws heavily on the commissioned paper, by Grenzeback and Lukmann (2007).

destroyed, necessitating rerouting of traffic and placing increased strain on other routes, particularly other rail lines. Barge shipping was halted, as was export grain traffic out of the Port of New Orleans, the nation's largest export grain port. The pipeline network was shut down, producing shortages of natural gas and petroleum products.

Despite predictions of long-lasting transportation stoppages, however, the majority of the Gulf Coast highways, rail lines, pipelines, ports, and airports were back in service within weeks to a month (see Table 3-2). The worst-damaged bridges took 3 to 6 months to repair. Just three bridges that carry highway US-90 along the edge of the Gulf Coast failed to reopen until mid- to late 2007, approximately 2 years after they were destroyed.

The fact that Hurricanes Katrina and Rita had only a modest impact on national-level freight flows can be attributed primarily to redundancies in the transportation system, the timing of the storms, and the track of Hurricane Rita. For example, truck traffic was diverted from the collapsed bridge that carries highway I-10 over Lake Pontchartrain to highway I-12, which parallels I-10 well north of the Gulf Coast. The primary north–south highways that connect the Gulf Coast with the major inland transportation hubs were not damaged and were open for nearly full commercial freight movement within days. The railroads were able to reroute intermodal and carload traffic not bound directly for New Orleans through Memphis and other Midwest rail hubs. Although New Orleans is a major rail freight interchange point for east–west rail traffic, it is not itself a major origin or destination for rail freight. Had Hurricane Rita struck a larger industrial and transportation hub such as Houston, the effects on rail transportation and freight movement would have been greater and more costly. Timing also played a role. The hurricanes struck before the peak of the corn and soybean export season. Most of the Mississippi River ports and the inland waterway were back in service to handle peak export demand later in fall 2005. Finally, the major pipelines suffered relatively little damage and were able to open within days, as electrical power was restored.

The hurricanes' impacts on national freight flows may have been modest, but they were certainly not without cost. A full accounting of the direct costs to repair transportation facilities damaged by Hurricanes Katrina and Rita has not yet been compiled. Reported costs of individual projects shown in Table 3-2 total more than \$1.1 billion. Replacement of the I-10 Twin Span Bridge between New Orleans and Slidell, Louisiana, will add nearly another \$1 billion, and the repair and replacement of rail lines, pipelines, ports, waterways, and airports will likely add several billion more to the total. Moreover, the numbers do not include the costs of unreported emergency operating expenditures, lengthy detours, the opportunity costs of lost shipments, and the long-term costs of displaced business and trade.

What lessons were learned about the vulnerability of the transportation system from the experience with these two hurricanes? First, with few exceptions, the physical redundancies of a mature transportation system provided sufficient alternative routes to keep freight flows moving without major disruption. Where the infrastructure was privately owned (e.g., CSX Railroad), arrangements with other carriers enabled operations to continue. Of course, this outcome might be quite different if multiple catastrophic storms were to strike major industrial and transportation hubs in close succession—a plausible scenario in a climate-changed world. Second, restoration of transportation services depended heavily on the availability of electrical power and manpower. Electricity is critical for the highway system to operate traffic lights and signs, for railroads to operate signal systems and crossing gates, for ports to operate cranes and elevators, for airports to power air traffic control facilities and operate nighttime runway lights, and for pipelines to power pumping stations. Thus, redundancy of power and communications systems is also necessary for the rapid restoration and functioning of freight transportation networks. Similarly, adequate manpower is critical to timely efforts to restore transportation services and staff restoration projects. Because of the devastation wreaked by Hurricane Katrina, many public- and private-sector employees lost family and homes in the storm, and many others evacuated the region; New Orleans itself was closed for more than a month. Thus, major transportation companies such as CSX were forced to bring in workers from other locations to staff reconstruction projects.

Finally, the storms have resulted in plans for relocating at least one facility and redesigning others in anticipation of future hurricanes. The Port of New Orleans is considering relocating companies and facilities to the main port area on the Mississippi riverfront from the deep-water channel connecting the port's Inner Harbor navigation canal to the Gulf, where they are more vulnerable to future storms. The cost of the relocation is estimated at $350 million. CSX has considered moving its vulnerable rail line inland—less as a response to hurricane threats than as a response to Mississippi politicians who are interested in the land for casino and housing development (M. Hinsdale, CSX, personal communication, Sept. 12,

TABLE 3-2 **Major Transportation Facilities Damaged and Closed by Hurricanes Katrina and Rita**

Element of Infrastructure	Issue	Cost to Repair ($ millions)	Closed On	Closed Until
Highways				
I-10 (Louisiana and Mississippi)				
Twin Span Bridge (New Orleans, Louisiana–Slidell, Louisiana)		35.0		
Eastbound span	Heavily damaged (collapsed spans)		Aug. 29, 2005	Oct. 14, 2005
Westbound span	Heavily damaged (collapsed spans)		Aug. 29, 2005	Jan. 6, 2005
I-10 to US-90 ramp bridges (Mobile Bay, Alabama)	Damaged	0.4	Aug. 29, 2005	
Pascagoula River Bridge Eastbound (Jackson County, Mississippi)	312-ft section damaged	5.2	Aug. 29, 2005	Oct. 1, 2005
US-90 (Louisiana, Mississippi, and Alabama)				
Chef Menteur Pass Bridge (East New Orleans, Louisiana)	Damaged	2.9	Aug. 29, 2005	Aug. 2007
Rigolets Bridge (East New Orleans, Louisiana)	Electrical/mechanical damage	44.0	Aug. 29, 2005	Dec. 7, 2005
Bay St. Louis Bridge (Bay St. Louis, Mississippi–Pass Christian, Mississippi)	Destroyed	266.8	Aug. 29, 2005	May 2007
Roadway (Pass Christian, Mississippi–Ocean Springs, Mississippi)	Heavily damaged	100.0	Aug. 29, 2005	Oct. 29, 2005
Biloxi–Ocean Springs Bridge (Biloxi, Mississippi–Ocean Springs, Mississippi)	Destroyed	338.6	Aug. 29, 2005	Nov. 2007
Cochrane–Africatown Bridge (Mobile, Alabama)	Damaged (oil rig)	1.7	Aug. 29, 2005	Sept. 1, 2005
Mobile Causeway/Tensaw Bridge (Mobile Co./Baldwin Co., Alabama)	Damaged		Aug. 29, 2005	Sept. 2, 2005
Lake Pontchartrain Causeway (Louisiana)				
Northbound span	Undamaged		Aug. 29, 2005	Not closed
Southbound span	Damaged		Aug. 29, 2005	Sept. 24, 2005
I-110 (Biloxi, Mississippi)	Damaged	5.0	Aug. 29, 2005	Sept. 1, 2005
LA-1	Damaged		Aug. 29, 2005	

	Aug. 29	Sept. 5	Sept. 12	Sept. 19	Sept. 26	Oct. 3	Oct. 10	Oct. 17	Oct. 24	Oct. 31	Nov. 7	Nov. 14	Nov. 21	Nov. 28	Dec. 5	Dec. 12	Dec. 19	Dec. 26	Jan. 2	Jan. 9	Jan. 16	Jan. 23	Jan. 30	Feb. 6	Feb. 13	Feb. 20	Feb. 27
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TABLE 3-2 *(continued)* **Major Transportation Facilities Damaged and Closed by Hurricanes Katrina and Rita**

Element of Infrastructure	Issue	Cost to Repair ($ millions)	Closed On	Closed Until
Rail Corridors				
CSX: Gulf Coast Mainline (New Orleans, Louisiana–Pascagoula, Mississippi)	Heavily damaged	250.0	Aug. 29, 2005	Jan. 31, 2006
Norfolk Southern: Lake Pontchartrain Bridge	Washed out		Aug. 27, 2005	Sept. 12, 2005
Union Pacific	Minor damage		Aug. 29, 2005	Aug. 31, 2005
Burlington Northern Santa Fe: Bayou Boeuf Bridge	Minor damage		Aug. 29, 2005	Sept. 1, 2005
Canadian National	Minor damage		Aug. 29, 2005	Sept. 30, 2005
Kansas City Southern	Undamaged		Aug. 29, 2005	Aug. 31, 2005
Pipelines				
Louisiana Offshore Oil Port	Minor damage		Aug. 28, 2005	Sept. 2, 2005
Capline	Mostly affected by power outages		Aug. 28, 2005	Sept. 1, 2005
Colonial Pipeline	Mostly affected by power outages		Aug. 28, 2005	Aug. 31, 2005
Plantation Pipeline	Mostly affected by power outages		Aug. 28, 2005	Sept. 1, 2005
Ports				
Port of New Orleans	Significant damage		Aug. 28, 2005	Sept. 12, 2005
175 barges stranded in New Orleans	Out of commission	7.6		
Port of South Louisiana	Damaged		Aug. 28, 2005	
Port Fourchon	Damaged		Aug. 28, 2005	
Port of Gulfport	Mostly destroyed		Aug. 28, 2005	Sept. 30, 2005
Port of Lake Charles	Minor damage		Sept. 22, 2005[a]	Oct. 1, 2005
Port of Houston	Undamaged		Sept. 22, 2005[a]	Sept. 27, 2005
Aviation				
Louis Armstrong New Orleans International Airport	Heavily damaged	15.2	Aug. 28, 2005	Sept. 13, 2005
Lakefront Airport	Heavily damaged	2.0	Aug. 28, 2005	Oct. 19, 2005
Gulfport–Biloxi International Airport	Heavily damaged	44.0	Aug. 28, 2005	Sept. 8, 2005
Lake Charles Regional Airport	Heavily damaged	8.0	Sept. 22, 2005[a]	Sept. 28, 2005
Southeast Texas Regional Airport	Damaged	6.0	Sept. 22, 2005[a]	Oct. 8, 2005

■ Duration of facility closure; now reopened. ▨ Duration of facility closure; still closed for repair or replacement.

□ Partially closed.

[a] Closures caused by Hurricane Rita; all others caused by Hurricane Katrina.

Source: Grenzeback and Lukmann 2007, 40.

	Aug. 29	Sept. 5	Sept. 12	Sept. 19	Sept. 26	Oct. 3	Oct. 10	Oct. 17	Oct. 24	Oct. 31	Nov. 7	Nov. 14	Nov. 21	Nov. 28	Dec. 5	Dec. 12	Dec. 19	Dec. 26	Jan. 2	Jan. 9	Jan. 16	Jan. 23	Jan. 30	Feb. 6	Feb. 13	Feb. 20	Feb. 27
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2006). And at the initiative and recommendation of the Federal Highway Administration (FHWA), almost all of the major river and bay bridges destroyed by the hurricane's surge waters will be rebuilt at higher elevations, above the maximum forecast surge levels.[27]

FINDINGS

All modes of transportation are vulnerable to climate change. Just as infrastructure is local and regional, however, so, too, are the impacts of climate change. They will vary depending on the location, mode, and condition of the transportation infrastructure. For example, coastal areas and their infrastructure will be subject to the impacts of sea level rise, while the St. Lawrence Seaway and the Great Lakes may experience lower water levels. The infrastructure will experience impacts unique to each mode (e.g., scour on bridge supports), but many impacts, such as flooding and erosion, will be common across all modes. The condition of the infrastructure itself will affect the impacts experienced. Increased intense precipitation, for example, could cause accelerated degradation of the surfaces of roads in poor condition. As the examples in this chapter have illustrated, the impacts of climate change on U.S. transportation will be widespread and costly.

According to the most recent scientific assessment, the IPCC Fourth Assessment Report, the greatest impact of climate change on North America's transportation system will be coastal flooding, especially along the Gulf and Atlantic Coasts, because of sea level rise, aggravated in some locations by land subsidence and storm surge (Burkett 2002). However, the rate at which these changes are likely to occur remains uncertain. The current IPCC projections do not include melting of the Greenland ice mass, for example, which could accelerate sea level rise.

Projected climate extremes are likely to have a particularly severe impact on transportation infrastructure because the U.S. transportation system was built to typical weather conditions at the time and local weather and climate

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[27] Hurricane damage to the Gulf Coast bridges resulted primarily from a combination of storm surge and wave crests that simply lifted bridge decks off their supports. Thus, FHWA recommended that a 100-year rather than a 50-year design frequency be used for Interstates, major structures, and critical bridges and that design guidelines take into consideration a combination of wave and surge effects. It was also recommended that risk and cost assessments be conducted (FHWA 2005 in Meyer 2006). New standards have not yet been agreed upon, so it is unclear whether they will take forecasts of sea level rise into consideration.

experience. Expected changes in climate extremes, such as more extreme temperatures, more intense precipitation, and more intense storms, could push environmental conditions outside the range for which the system was designed. This in turn could necessitate changes in design, materials, construction, and operating and maintenance practices. For example, increased flooding from more intense storms could require a combination of physical improvements (e.g., greater pumping capacity, more elevated bridges) and operational measures (e.g., better flood warning and evacuation plans, better real-time micro-level weather forecasts).

Climate change will create both winners and losers. For example, the marine transportation sector could benefit from more open seas in the Arctic, reducing shipping routes, times, and costs in the long run. In cold regions, expected temperature warming, particularly decreases in very cold days and later onset of seasonal freeze and earlier onset of seasonal thaw, could mean less snow and ice control for departments of transportation and safer travel conditions for passenger vehicles and freight.

In all cases, transportation professionals will have to confront and adapt to climate change without knowing the full magnitude of expected changes. The greatest challenge is the uncertainty as to exactly what changes to expect and when. Thus, transportation decision makers will need to adopt a more probabilistic risk management approach to infrastructure planning, design, and operations to accommodate uncertainties about the nature and timing of expected climate changes—a major focus of the next chapter.

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Abbreviations

ACIA	Arctic Climate Impact Assessment
BTS	Bureau of Transportation Statistics
CBO	Congressional Budget Office
FHWA	Federal Highway Administration
NOAA	National Oceanic and Atmospheric Administration
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
USDOT	U.S. Department of Transportation

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ANNEX 3-1 **Potential Climate Changes and Impacts on Transportation**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Impacts on Marine Transportation		Impacts on Air Transportation	
Potential Climate Change	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure
Temperature: increases in very hot days and heat waves	Limitations on periods of construction activity due to health and safety concerns; restrictions typically begin at 29.5°C (85°F); heat exhaustion possible at 40.5°C (105°F) Vehicle overheating and tire deterioration	Impacts on pavement and concrete construction practices Thermal expansion on bridge expansion joints and paved surfaces Impacts on landscaping in highway and street rights-of-way Concerns regarding pavement integrity, e.g., softening, traffic-related rutting, migration of liquid asphalt;	Impacts on shipping due to warmer water in rivers and lakes		Delays due to excessive heat Impact on lift-off load limits at high-altitude or hot-weather airports with insufficient runway lengths, resulting in flight cancellations and/or limits on payload (i.e., weight restrictions) More energy consumption on the ground	Heat-related weathering and buckling of pavements and concrete facilities Heat-related weathering of vehicle stock

(continued)

ANNEX 3-1 *(continued)* **Potential Climate Changes and Impacts on Transportation**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Impacts on Marine Transportation		Impacts on Air Transportation	
Potential Climate Change	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure
		sustained air temperature over 32°C (90°F) is a significant threshold Rail-track deformities; air temperature above 43°C (110°F) can lead to equipment failure				
Temperature: decreases in very cold days	Regional changes in snow and ice removal costs and environmental impacts from salt and chemical use (reduction overall, but increases in some regions)	Decreased utility of unimproved roads that rely on frozen ground for passage	Less ice accumulation on vessels, decks, riggings, and docks; less ice fog; fewer ice jams in ports		Changes in snow and ice removal costs and environmental impacts from salt and chemical use Reduction in need for deicing Fewer limitations on ground crew	

	Fewer cold-related restrictions for maintenance workers				work at airports, typically restricted at wind chills below –29°C (–20°F)	
Temperature: increases in Arctic temperatures		Thawing of permafrost, causing subsidence of roads, rail beds, bridge supports (cave-in), and pipelines Shorter season for ice roads	Longer ocean transport season and more ice-free ports in northern regions Possible availability of a Northern Sea Route or a Northwest Passage			Thawing of permafrost, undermining runway foundations
Temperature: later onset of seasonal freeze and earlier onset of seasonal thaw	Changes in seasonal weight restrictions Changes in seasonal fuel requirements Improved mobility and safety associated with a reduction in winter weather Longer construction season	Reduced pavement deterioration resulting from less exposure to freezing, snow, and ice, but possibility of more freeze–thaw conditions in some locations	Extended shipping season for inland waterways (especially the St. Lawrence Seaway and the Great Lakes) due to reduced ice coverage			

(continued)

ANNEX 3-1 *(continued)* **Potential Climate Changes and Impacts on Transportation**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Impacts on Marine Transportation		Impacts on Air Transportation	
Potential Climate Change	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure
Sea level rise, added to storm surge	More frequent interruptions in travel on coastal and low-lying roadways and rail service due to storm surges More severe storm surges, requiring evacuation	Inundation of roads and rail lines in coastal areas More frequent or severe flooding of underground tunnels and low-lying infrastructure Erosion of road base and bridge supports Bridge scour Reduced clearance under bridges Loss of coastal wetlands and barrier shoreline Land subsidence	More severe storm surges, requiring evacuation	Changes in harbor and port facilities to accommodate higher tides and storm surges Reduced clearance under waterway bridges Changes in navigability of channels; some will be more accessible (and farther inland) because of deeper waters, while others will be restricted because of changes in sedimentation rates and shoal locations	Potential for closure or restrictions for several of the top 50 airports that lie in coastal zones, affecting service to the highest-density populations in the United States	Inundation of airport runways located in coastal areas

Precipitation: increase in intense precipitation events	Increases in weather-related delays Increases in traffic disruptions Increased flooding of evacuation routes Disruption of construction activities Changes in rain, snowfall, and seasonal flooding that affect safety and maintenance operations	Increases in flooding of roadways, rail lines, and subterranean tunnels Overloading of drainage systems, causing backups and street flooding Increases in road washout, damages to rail bed support structures, and landslides and mudslides that damage roadways and tracks Impacts on soil moisture levels, affecting structural integrity of roads, bridges, and tunnels Adverse impacts of standing water on the road base	Increases in weather-related delays	Impacts on harbor infrastructure from wave damage and storm surges Changes in underwater surface and silt and debris buildup, which can affect channel depth	Increases in delays due to convective weather Storm water runoff that exceeds the capacity of collection systems, causing flooding, delays, and airport closings Implications for emergency evacuation planning, facility maintenance, and safety management	Impacts on structural integrity of airport facilities Destruction or disabling of navigation aid instruments Runway and other infrastructure damage due to flooding Inadequate or damaged pavement drainage systems

(continued)

ANNEX 3-1 *(continued)* **Potential Climate Changes and Impacts on Transportation**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Impacts on Marine Transportation		Impacts on Air Transportation	
Potential Climate Change	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure	Operations and Interruptions	Infrastructure
		Increases in scouring of pipeline roadbeds and damages to pipelines				
Precipitation: increases in drought conditions for some regions	Increased susceptibility to wildfires, causing road closures due to fire threat or reduced visibility	Increased susceptibility to wildfires that threaten transportation infrastructure directly Increased susceptibility to mudslides in areas deforested by wildfires	Impacts on river transportation routes and seasons		Decreased visibility for airports located in drought-susceptible areas with potential for increased wildfires	
Precipitation: changes in seasonal precipitation and river flow patterns	Benefits for safety and reduced interruptions if frozen precipitation shifts to	Increased risk of floods from runoff, landslides, slope failures, and	Periodic channel closings or restrictions if flooding increases	Changes in silt deposition leading to reduced depth of some inland waterways and	Benefits for safety and reduced interruptions if frozen precipitation shifts to rainfall	Inadequate or damaged pavement drainage systems

	rainfall, depending on terrain	damage to roads if precipitation changes from snow to rain in winter and spring thaws	Benefits for safety and reduced interruptions if frozen precipitation shifts to rainfall	impacts on long-term viability of some inland navigation routes		
Storms: more frequent strong hurricanes (Category 4–5)	More debris on roads and rail lines, interrupting travel and shipping More frequent and potentially more extensive emergency evacuations	Greater probability of infrastructure failures Increased threat to stability of bridge decks Increased damage to signs, lighting fixtures, and supports Decreased expected lifetime of highways exposed to storm surge	Implications for emergency evacuation planning, facility maintenance, and safety management	Greater challenge to robustness of infrastructure Damage to harbor infrastructure from waves and storm surges Damage to cranes and other dock and terminal facilities	More frequent interruptions in air service	Damage to landside facilities (e.g., terminals, navigation aids, fencing around perimeters, signs)

4

Challenges to Response

This chapter explores the challenges and constraints faced by transportation professionals as they begin to confront projected impacts of climate change. The chapter begins with an overview of how the U.S. transportation system is organized and how investment and operating decisions are made. These organizational arrangements and planning approaches influence how transportation decision makers consider the issue of climate change and help explain why responding poses difficult challenges—the next topic of discussion. A framework for addressing the uncertainties and analyzing the trade-offs associated with adaptation to climate change is then introduced. The chapter ends with the committee's findings, suggesting opportunities for meeting the challenges to response.

DECISION MAKING IN THE TRANSPORTATION SECTOR

Organization and Funding

Responsibility for transportation infrastructure is decentralized and shared between the public and private sectors (see Table 4-1). Highways, bridges, and public transportation infrastructure are owned and operated by state and local governments.[1] Major funding for capital improvements—and in the case of public transportation, rolling stock (e.g., transit buses, railcars)—is provided by the federal government, with matching

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[1] Highways and bridges on federal lands are an exception, as are privately owned toll roads. In addition, the vehicles that use the highway system are privately owned, except for transit buses (see Table 4-1).

TABLE 4-1 **Transportation System Responsibility**

System	Owner–Operators	Capital Improvements
Land Transportation		
Highways and bridges		
Infrastructure	State and local governments[a]	Federal funding for major highways with required local match
Vehicles	Privately owned and operated	NA
Public transportation		
Infrastructure	Local governments and independent authorities[b]	Federal funding with required local match
Rolling stock	Publicly owned and operated	NA
Railroads		
Infrastructure	Privately owned and operated	Private funding
Rolling stock	Privately owned and operated	NA
Pipelines	Privately owned and operated	Private funding
Marine Transportation		
Inland and coastal navigation channels, St. Lawrence Seaway, and associated navigation aid (all infrastructure)	Federal government through the U.S. Army Corps of Engineers and U.S. Coast Guard	Joint federal and nonfederal public funding, user fees
Ports and terminals		
Infrastructure	State and local governments, independent authorities, and private entities	Public and private funding
Vessels	Privately owned and operated	NA
Air Transportation		
Infrastructure	Local governments and independent authorities	Federal funding, supplemented with state and local grants and passenger facility charges
Vehicle fleet	Privately owned and operated	NA

Note: NA = not applicable.

[a] The exceptions are highways on federal lands and private toll roads. States are responsible for highways and bridges on major roads. Cities are responsible for major arterial streets in some metropolitan areas.

[b] Some public transportation services are contracted out to private providers.

requirements from other governmental levels. Railroads and pipelines are privately owned and operated, although the federal government has regulatory oversight over railroad and pipeline safety.[2] Ports are joint public–private operations. Typically, an independent authority or public entity owns the land and sometimes the landside facilities, which are then leased to private operators, generally on a long-term basis. Major improvements, such as dredging of harbors and channels, are federally funded through the U.S. Army Corps of Engineers, with required cost sharing.[3] The St. Lawrence Seaway system is jointly operated by the U.S. government and Canada through management corporations established expressly for this purpose, while the inland waterway system, including upkeep of the lock system, is operated by the U.S. government through the U.S. Army Corps of Engineers, also with cost-sharing arrangements. Airports are publicly owned and operated by local governments or independent authorities. At the major hub airports, the airlines often operate their own hangars and maintenance facilities. Many airport capital improvements are federally funded, supplemented with state and local grants and passenger facility charges. In sum, decision making in the transportation sector is a shared responsibility among many governmental owner–operators and the private sector, largely decentralized, and modally focused.

Infrastructure Service Lives

Transportation infrastructure is designed to perform for a wide range of service lives (see Table 4-2).[4] Roads are among the shortest-lived facilities, with surfaces that must be repaved every 10 to 20 years.[5] Bridges, locks, and pipelines are among the longest-lived—designed for a 50- to 100-year service life—although many of their components (e.g., bridge decks) must be rehabilitated more frequently. Transportation facilities

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[2] The Federal Energy Regulatory Commission regulates the siting of new natural gas pipelines, and the U.S. Department of Transportation requires 3 feet of cover at initial construction of an oil pipeline.

[3] There is some privately constructed and maintained infrastructure (e.g., channels to private terminals, private berthing areas).

[4] Service life can be defined as the length of time a facility will remain in use to serve its intended function. This will often exceed the facility's design life or the period of time used for economic analysis of project benefits and costs.

[5] Typically, the road base is far more durable, unless it is compromised by poor drainage or other adverse conditions.

TABLE 4-2 **Transportation Infrastructure Design Lives**

Transportation Mode	Expected Infrastructure Design Life (years)
Highways, bridges, and tunnels	
Pavement	10–20
Bridges/culverts	50–100/30–45
Tunnels	50–100
Public transportation	
Rail track	Up to 50
Rail	
Track	Up to 50
Marine transportation	
Locks and dams	50
Docks and port terminals	40–50
Air transportation	
Runway pavements	10
Terminals	40–50
Pipeline	100

Note: Design lives are averages. Much of the infrastructure operates far beyond its design life.

Source: Meyer 2006.

with shorter design lives provide numerous opportunities for engineers to adapt to the impacts of climate change, such as by use of more heat-resistant paving materials to withstand the more extreme temperatures projected for some U.S. regions. Opportunities for adaptation—for example, elevating a bridge to accommodate expected sea level rise—are fewer for longer-lived facilities, which are rehabilitated or retrofitted at much longer intervals.

In practice, many transportation facilities perform well beyond their design lives. Moreover, the most critical decision is where to locate a facility initially. Once the right-of-way and alignment for a facility have been established, such as for a highway or rail line, relocating the right-of-way, as might be required in coastal areas experiencing sea level rise, would be enormously expensive. Thus, investment choices made today about the location, retrofitting, and rehabilitation of transportation infrastructure will have far-reaching consequences for the ability of transportation infrastructure to accommodate climate change and for the costs of any necessary adaptation.

Long-Range Planning and Investment Decisions

For each mode, transportation professionals engage in planning for long-term capital improvements to infrastructure assets. Below is a brief summary of the planning process for publicly and privately owned infrastructure and the implications for addressing climate change.

Publicly Owned Infrastructure

Planning and investment decisions for publicly owned land transportation infrastructure are made within the framework and requirements defined by the planning provisions contained in legislation; codified in Title 23, U.S.C.; and most recently amended in August 2005 by the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, known as SAFETEA-LU. State departments of transportation and metropolitan planning organizations (MPOs), working in coordination with local governments, have lead responsibilities for planning.[6] The transportation planning process has two principal products: a long-range transportation plan and a short-term transportation improvement program. Because the infrastructure is largely in place, the vast majority of capital improvement projects involve retrofitting or upgrading the existing transportation system or providing new capacity at the margin.

Each state and metropolitan area with an MPO prepares a long-range plan, looking ahead 20 to 30 years. The plans incorporate forecasts of population, economic growth, and land use patterns to help determine the locus and extent of demand for passenger and freight travel and supporting transportation infrastructure needs. The second product—a transportation improvement program—provides a list of short-term capital improvement projects, reflecting available funding, which is updated on a 4-year cycle.

Joint Public–Private and Privately Owned Infrastructure

Ports generally have a short planning horizon—5 to 10 years—because of the highly competitive nature of port business operations. Analyses of major capital improvements, however, such as landside facilities—warehouses,

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[6] The Highway Act of 1973 required the establishment of MPOs in urbanized areas with a population of more than 50,000 and dedicated a small portion of each state's funding from the Highway Trust Fund for this purpose. MPOs are composed primarily of local elected officials whose purpose is to facilitate decision making on regional transportation issues.

terminals, berths, rail links, and truck access roads—many of which have 40- to 50-year design lives, require forecasting of costs and expected returns over a much longer planning period. Similarly, the planning horizon for capital improvements to long-lived locks and dams along inland waterways is about 50 years.

Airports have 20- to 30-year capital improvement plans for landside investments. Because many of these improvements are federally financed, the Federal Aviation Administration, as well as local airport authorities and local planners, is involved in the development of long-range plans for airport infrastructure.

The planning cycle for privately owned infrastructure—railroads and pipelines—is handled by individual companies through their capital budgeting process. Railroads are characterized by their capital intensity and large fixed investments. Even when a fully functional network is in place, large annual capital investments must be made to provide operating equipment (e.g., locomotives, freight cars, maintenance vehicles, computer and signaling equipment) and maintain the physical right-of-way.[7] Capital budgets are part of strategic plans that look 5 years out and annual financial plans that identify the available budget for capital outlays each year. Analyses of individual capital projects forecast costs and returns over 20- to more than 30-year lifetimes for major facilities, such as a double-tracking project or a new marshaling yard.[8]

Pipelines involve a large initial investment; assets are designed to be very long-lived (about 100 years); and there are few new entrants. Pipeline companies conduct market forecasts looking ahead 5 years at most. Planning for capital improvements follows the normal private-sector capital budgeting process (i.e., project analysis using present value calculations over asset lifetimes, minimum expected rates of return for project selection, and annual capital budgets).

In sum, public and private transportation infrastructure providers are making short- and long-term investment decisions every day that have implications for how well the transportation system will respond to climate change in both the near and long terms.

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[7] These investments tend to be uneven or “lumpy,” however, because equipment, such as railcars, is purchased in batches.

[8] Note, however, that discounting of future benefits at typical discount rates means that for financial purposes, benefits beyond, say, 20 years will be of diminishing importance.

Operational and Emergency Planning

Transportation professionals in both the public and private sectors also engage in operational planning to respond to short-term congestion, delays, and disruptions to system operations. Transportation professionals are keenly aware of the effects of weather on system performance and already address the impacts of weather on operations for a diverse range of climate conditions. For example, many departments of transportation have well-organized snow and ice control operations that can consume up to 40 percent of annual highway operating budgets in some northern U.S. states. Others are organizing to achieve better management of traffic congestion and incident control by establishing transportation management centers.[9]

Climate changes are expected to affect transportation primarily through climate extremes, such as more severe tropical storms and flooding from intense rainfall. One of the probable outcomes is the growing importance of transportation to emergency response and evacuation. The organizational arrangements necessary to support this interaction are generally not well developed, although some regions have been more proactive in this regard. For example, Florida has a well-organized multigovernmental approach to emergency planning and evacuation for hurricanes that includes transportation. Hurricanes Katrina and Rita provided a wake-up call to many governments in the Gulf Coast region, which have since improved emergency plans and evacuation strategies. The events of September 11, 2001, were instrumental in focusing attention on the need for emergency plans and evacuation strategies and in underscoring the critical support transportation can provide. In practice, however, transportation is not always well integrated into these plans. Emergencies that involve multistate geographic areas and require a regional response are particularly difficult, as Hurricane Katrina illustrated (Deen 2006).

In the longer term, critical infrastructure that serves as evacuation routes or egress points may itself be threatened by climate change. For example, highways in low-lying coastal areas could become endangered as encroaching sea level rise combines with storm surge to make these routes impassable.

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[9] For more detail, see the paper by Lockwood (2006) commissioned for this study. See also the discussion about transportation management centers in Chapter 5 (Box 5-1).

CHALLENGES POSED BY CLIMATE CHANGE

Climate change poses a complex set of challenges that in many ways are new and different for transportation planners and decision makers, and this may help explain why there is little consensus on the issue or how to address it.[10] The lack of a consistent response may also stem from resource constraints and an absence of adequate information and guidance.

Differences in Planning Horizons

Climate scientists describe the future in terms of outcomes that unfold over decades to centuries. One of the reasons for these long time frames is that the inherent variability of the climate makes it difficult to separate the "signal from the noise" in making short-term (i.e., less than 25 years) projections. For many public-sector transportation planners, long-term planning horizons rarely exceed more than 30 years; 20 to 25 years is the norm. Port, rail, and pipeline providers have much shorter planning horizons—5 years at most for strategic plans—although many of their assets are designed to be much longer-lived, and capital project analyses reflect these longer time frames. Thus, many transportation planners perceive that impacts of climate change will be experienced well beyond the time frame of their longest-term plans, not realizing that climate changes are already occurring and that investment decisions made today will affect how well the infrastructure accommodates these and future changes.

Treatment of Uncertainty

The issue of climate change introduces uncertainties with which transportation planners are unfamiliar and uncomfortable. Climate scientists describe the future in probabilistic terms with a portfolio of plausible scenarios and outcomes that are constantly refined and revised as new knowledge accumulates. Uncertainties exist with regard to the rate of climate change and the extent of its impacts, even for those changes about which climate scientists have the greatest confidence, such as warming temperatures and sea level rise. These uncertainties make it difficult to

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[10] See the paper by Dewar and Wachs (2006) commissioned for this study for a more complete discussion of many points made in this section.

plan and design infrastructure that can accommodate these impacts. The likelihood of climate extremes and surprises only exacerbates the problem. Moreover, knowledge about climate change impacts is likely to change over time, requiring a dynamic decision process that can adapt to new information and accommodate feedback.

In contrast to climate scientists, transportation professionals tend to focus on "knowns." Metropolitan transportation planners, for example, typically provide a single vision of the future on the basis of "best available" forecasts of population, employment, housing, and development that drive transportation infrastructure needs. Infrastructure is built to meet the forecast demand, often without fully incorporating uncertainties associated with the predictions. Unexpected, unplanned events, such as earthquakes, hurricanes, and floods, challenge the system, but a combination of traveler adaptability and system redundancy has enabled transportation infrastructure providers thus far to maintain operations with surprisingly little disruption.

Perhaps for these reasons, regional transportation planners appear to be satisfied with their performance. A national survey of regional planning agencies, for example, revealed that the majority rated their performance as acceptable and their models as adequate or better. Only a few, however, had simulated the effects of removing key links from their systems or assuming large and irregular fluctuations in traffic flows in some corridors, such as might occur if tropical storms become more severe or intense precipitation and flooding become more frequent in some regions (Dewar and Wachs 2006).

Poor Alignment Between Climate Change Impacts and Transportation Organizational Arrangements

The decentralized and modally focused organizational structure of the transportation sector may not align well with climate change impacts, which do not always follow modal, jurisdictional, or corporate boundaries. Sea level rise and flooding from intense precipitation, for example, can affect individual transportation facilities, but they are also likely to have widespread impacts requiring the response of multiple infrastructure providers. Some climate changes, such as more frequent intense tropical storms (Category 4–5 hurricanes), will require regional or even multistate responses that transportation institutions are poorly configured to address.

Regional planning organizations exist, but regional government does not. Multistate action is difficult, as Hurricane Katrina illustrated.

Resource Constraints

Climate change poses the possibility of significant, long-lasting impacts on transportation infrastructure and system performance that are likely to be widespread and costly in human and economic terms. Most other challenges confronted by the transportation sector, even extreme weather events such as Hurricane Katrina or earthquakes, cause significant damage, but the effects tend to be local and temporary. By contrast, climate changes in some U.S. regions may necessitate permanent changes. Over time, for example, roads, rail lines, and airport runways in low-lying coastal areas may become casualties of sea level rise, ultimately requiring relocation or expensive protective measures (e.g., levees, which themselves would be subject to catastrophic failure, as was experienced during Hurricane Katrina).

Resistance to Change

Transportation planners and engineers typically extrapolate from historical trends to forecast future trends and conditions that influence their investment choices and operating plans. However, the past will not be a reliable guide for future plans and designs as they relate to climate. Climate scientists caution that climate change will usher in a new regime of weather and climate extremes, likely falling outside the range for which many existing transportation facilities were designed.

Faced with a new problem such as this predicted break in trend, transportation professionals typically adopt incremental rather than radical solutions. This tendency to favor proven methods and practices is understandable, particularly for engineers, who are designing infrastructure expected to provide reliable service for decades, and in view of the uncertainties about the rate of climate change and the magnitude of its effects. Nevertheless, reinforced by conservative institutions, regulatory requirements, and limited funding, this way of thinking can hamper timely responses to issues such as climate change that involve risk and uncertainty.

Interviews with transportation planning officials conducted for the U.S. Department of Transportation's (USDOT's) Gulf Coast study by Cambridge Systematics, Inc. (2006) are illustrative of prevailing attitudes.

The interviews were conducted in spring 2006, when the impacts of Hurricanes Katrina and Rita were very much on the minds of local planners. Understandably, local officials were concerned with the immediate problems of rebuilding and recovery from the hurricanes. When questioned about the possibility that climate change could bring about more storms of the intensity of Katrina or Rita in the future, however, many local officials expressed skepticism or pleaded ignorance. Others opted for a literal interpretation of SAFETEA-LU's planning guidance, which does not require consideration of climate change, or pointed to federal policies that allow replacement of facilities only as they are currently designed, preventing consideration of design modifications that could provide for adaptation to potential climate change impacts (e.g., elevated bridges to accommodate sea level rise, storm surge, and wave action).[11] Some officials interviewed believed that Federal Highway Administration regulations prevented them from considering any changes that would extend beyond the time horizon of their long-range plans.[12] Still others identified limited current funding that, in combination with uncertainties about the rate and timing of projected climate changes, disinclines planners to give more attention to the issue.

Lack of Relevant Information

Even those transportation professionals who are aware of the importance of climate change and are already addressing its impacts, such as the planners and engineers in Alaska who are managing the effects of melting permafrost, indicate that they often lack sufficiently detailed information on which to take appropriate action. Climate scientists tend to describe projected climate changes in terms of global averages and confidence levels for global, continental, or large subcontinental regions because climate models have the greatest fidelity at these levels of analysis. In addition, studies of the impacts of climate change—with the exception of the handful of studies reviewed in the previous chapter—have not focused on

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[11] The Federal Highway Administration, however, has granted exceptions and is rethinking its regulations and guidance for design of bridges in a coastal environment (Meyer 2006).

[12] Section 6001 of SAFETEA-LU references a 20-year forecast period for long-range transportation plans. Many states and MPOs, however, are using a 20- to 30-year time horizon.

transportation specifically, but on other critical sectors, such as agriculture, forestry, energy, and water resources.

Transportation professionals need data at the finest-grained level of geographic detail possible because infrastructure is regional and local. Fortunately, the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC 2007) noted the improved capability of climate scientists to simulate regional climates and make robust statements about projected climate changes for many regions—a level of geographic specificity that is more useful to transportation planners and designers. Climate scientists should be encouraged to develop information on transportation-relevant climate changes that is as detailed as possible. Transportation professionals also have a role to play in helping to define what information about climate change they need, such as temperature and precipitation thresholds, climate conditions that create unacceptable performance outcomes, and the like.

A DECISION FRAMEWORK FOR ADDRESSING CLIMATE CHANGE

How should transportation planners and engineers proceed in view of the challenges just outlined? A decision-making framework is needed that more adequately accommodates uncertainty and incorporates more probabilistic approaches to assessing risk and making investment choices. The basic concepts in such a probabilistic assessment include hazards, assets, and consequences, each of which is subject to uncertainties (see Annex 4-1). In the context of climate change, the hazards represent the potential threats from changing climate conditions, such as more extreme temperatures or more intense tropical storms. The assets represent the infrastructure and its value—both its economic value to the performance of the transportation system and its physical replacement value. The consequences represent the susceptibility of the infrastructure to damage from the hazards, which in turn depends on the infrastructure's design and state of repair, among other factors. Estimating future risk involves solving for the probability of occurrence of the hazards times the probable consequences if the hazards occurred, summed over all the transportation assets in a region. The objective is to minimize future risks.

Transportation professionals already take risk into account, particularly in designing facilities, and in recent years more probabilistic approaches have been incorporated (Meyer 2006). For example, engineers design structures to withstand certain wind speeds on the basis of a probabilistic assessment of wind speed occurrence as measured by historical wind speed frequency. The 100-year storm is another example. Engineers often size the drainage capacity of a transportation facility to handle a storm so severe that it occurs, on average, just once in 100 years. Adapting risk-based approaches to account for climate change poses new challenges. First, historical experience will not be a reliable predictor of future climate conditions. Second, the hazards themselves are likely to change over time, but in ways that are not currently understood with any precision. Finally, attempting to hedge by simply designing to a more robust standard—say, a higher wind speed tolerance or a 500-year storm—will produce much more costly designs, likely to be unacceptable given limited budgets.[13] A more strategic and selective risk-based approach that explicitly trades off the costs of designing for greater resilience against the costs associated with failure could help in setting realistic design standards and investment priorities.

California's seismic retrofit program for bridges is an example of one way to proceed (see Box 4-1). Following the Loma Prieta earthquake in 1989, the state was faced with the daunting task of how best to retrofit its stock of some 25,000 bridges. Earthquakes are a recurring problem, but there is considerable uncertainty about when or where a seismic event will occur. Moreover, the resources needed to retrofit every bridge to the highest standard or to conduct a physical inventory of all structures to determine which need to be retrofit are not available. The California Department of Transportation decided to proceed in the following manner. First, departmental engineers determined an acceptable performance standard or level of risk, reducing one of the uncertainties. For most bridges, that standard was "no collapse" under a maximum seismic event, consistent with the geographic location of the bridge. The objective was to avoid loss of life. However, some damage to the structure was acceptable as long as the structure itself remained intact and could be reopened

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[13] The committee is aware of the precautionary principle, which holds that "where there are threats of serious or irreversible damage, the lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UNEP 1992 in Whiteside 2006). The committee recommends that cost-effective measures to protect the more vulnerable transportation infrastructure be taken. However, the significant costs of redesigning and retrofitting much of the infrastructure to adapt to potential climate change impacts underscore the need for more strategic and selective risk-based analyses.

Box 4-1

California Seismic Retrofit Program for Bridges

Following the Loma Prieta earthquake in 1989, the California Department of Transportation (Caltrans) faced the enormous task of prioritizing its inventory of structures throughout the state for seismic retrofit. Approximately 25,000 bridges on state and local highways required evaluation. Because of this large number of bridges, a simple and computationally manageable prioritization methodology had to be devised. The goal was to identify and rank the most seismically vulnerable bridges in the state so the available resources could be used in the most efficient manner possible.

The process began with establishing a required performance standard. For most bridges, the minimum standard was "no collapse" during a major seismic event to prevent loss of life. However, damage to the structure was acceptable provided that the structure itself remained intact and could be reopened for service soon after the event. The exceptions to the "no collapse" requirement were 750 structures for which the highest level of performance was desirable to protect the substantial investment in these major structures and ensure that they would remain in service after a major seismic event to provide access for emergency responders. The 11 major toll bridges, including the San Francisco–Oakland Bay Bridge, were handled separately because their complexity necessitated a time-consuming dynamic analysis.

A risk algorithm was developed for screening of the nontoll bridges. This algorithm was based on four major evaluation criteria: seismic activity, seismic hazard, impact, and vulnerability. Seismic activity was determined by locating structures in one of four fault activity zones, ranked from highly to minimally active. Seismic hazard was determined on the basis of specific conditions (e.g., soil) at the bridge site. Impact was based on such attributes as average daily traffic, route type, and detour length. Vulnerability was assessed on the basis of structural characteristics (e.g., structure type, structure age, presence of expansion joints) to assess the risk to the structure itself. The score on each criterion was multiplied by a weighting factor—seismic activity and hazard were weighted more heavily—and summed with those on the other criteria to arrive at a final score.

All 12,600 state highway bridges were processed by using this screening procedure and were prioritized by score. (The 750 major structures were flagged to be in the program.) Additional screening was required for 7,000

(continued)

Box 4-1 (continued)

California Seismic Retrofit Program for Bridges

bridges that failed to meet the minimum performance standard. These bridges were reviewed for specific deficiencies through an examination of the as-built plans for each. The second "paper" screening was used to determine whether the bridge was in the program or retrofit could be deferred; the goal was to make the program more manageable while still addressing the most urgent needs given the available resources. As a result of this second screening, 2,194 bridges were found to be in need of retrofit and were programmed for improvement. A final in-depth field inspection was performed, with the result that some bridges were found to meet the "no collapse" requirement and were removed from the list. A similar procedure was followed for the 12,400 local roadway bridges, resulting in 4,500 structures that required further evaluation and analysis.

Since the program was initiated, 2,194 bridges on the state highway system have been retrofit at a cost of $3 billion, and the program is considered 99 percent complete. The remaining phase of the program consists of retrofitting 1,235 bridges on local roadways at an estimated cost of $1.7 billion; the program for local bridges is about 60 percent complete. Funding is provided through a combination of local funds, state gas tax revenues, statewide bond initiatives, and federal funds.

Caltrans has maintained ongoing assessment of the seismic retrofit needs of its bridge inventory to identify structures with potential seismic vulnerabilities based on lessons learned since the program's inception. The bridges identified through this process are prioritized and added to the program as required.

State and local governments and private infrastructure providers could adopt a similar approach for identifying and screening critical infrastructure relative to projected climate changes. Key to adopting such an approach is establishing a performance standard for a particular facility that reflects a tolerable level of risk (a "no collapse" equivalent), along with a screening process that takes into consideration such factors as the degree of risk (e.g., magnitude of the hazard), the vulnerability of the facility, and how essential the facility is to the system so priorities for rehabilitation or retrofit can be determined.

Source: Information provided by Craig Whitten, Robert Stott, Kevin Thompson, and Cynthia MacLeay, Division of Engineering Services, Caltrans, October 2007.

for service soon after the event. The exceptions were 750 structures on state highways and 11 major toll bridges, which were held to a higher standard both to protect the substantial investment in these major structures and to ensure that these vital transportation lifelines would remain in service following a major seismic event to provide access for emergency responders. Second, the experts devised a layered screening system to rate the structures most in need of retrofit; an in-depth physical inventory was conducted only for those bridges that did not meet the performance standard. Finally, elected officials were brought on board, and a combination of funds—federal grants, state gas tax and bond funds, and local revenues—was employed to implement a long-term investment program that continues to this day.

State and local transportation officials could adopt a similar approach to assess how climate change may affect transportation assets and develop appropriate adaptation responses and investment strategies. To begin, they might ask the following questions:

- Which projected climate changes are most relevant for their region?
- How are climate change hazards likely to be manifested (e.g., flooding, storm surge coupled with sea level rise)?
- Which transportation assets may be affected?
- How severe must a hazard be before it becomes relevant and action is required? Can thresholds be identified?
- How likely is it that a projected hazard will exceed the threshold, when, and where?
- How much risk can be tolerated, or in other words, what infrastructure performance level is tolerable?
- What level of investment (capital and operating) is needed to maintain different levels of service? Can acceptable performance standards for all modes of transportation be established?
- Are there critical levels of service needed to protect health and safety?
- Who is empowered to make these judgments and decisions?
- What are the risks of adverse impacts or consequences if no action is taken?

Box 4-2

Decision Framework to Address Impacts of Climate Change on U.S. Transportation Infrastructure

1. Assess how climate changes are likely to affect various regions of the country and modes of transportation (assess hazards).
2. Inventory transportation infrastructure essential to maintaining network performance in light of climate change projections to determine whether, when, and where the impacts of projected changes could be consequential (assess the vulnerability of assets and the system's resilience to loss of assets).
3. Analyze adaptation options to assess the trade-offs between making the infrastructure more robust and the costs involved. Consider monitoring as an option.
4. Determine investment priorities, taking into consideration the criticality of the infrastructure component as well as opportunities for multiple benefits (e.g., congestion relief, removal of evacuation route bottlenecks).
5. Develop and implement a program of adaptation strategies for the near and long terms.
6. Periodically assess the effectiveness of adaptation strategies, and repeat Steps 1 through 5.

- If action is necessary, how will investment priorities be determined?
- Who will make the necessary investments, and how will they be funded?

Answers to many of these questions can be found by following the six steps set forth in Box 4-2. This approach provides guidance on how to proceed in addressing many of the technical questions previously posed. However, it does not cover relevant organizational and political issues. Transportation officials must communicate the results of their technical analyses to senior management and elected officials, who make the policy decisions that guide funding choices. In the California situation, the Loma Prieta earthquake focused attention on the need for seismic retrofit of many of the bridges throughout the state to avoid catastrophic failure and loss of life from such an event in the future. With climate changes, however, the impacts will not always be as unambiguously attributable to those changes or as dramatic, with the exception of extreme events (e.g., severe tropical storms, intense precipitation events, heat waves). Thus, communicating the need for early attention to the impacts of climate change requires leadership, supported by compelling analyses, on the part of the transportation community.

FINDINGS

Climate change poses a complex set of problems, associated risks, and uncertainties with which transportation planners and decision makers are unfamiliar. Among the characteristics of climate change that make it particularly difficult to tackle are uncertainties about the rate and extent of projected changes; the fact that climate change impacts may not follow the modal, jurisdictional, or corporate boundaries of the transportation sector; and the fact that impacts may require coordinated regional or multistate responses that infrastructure providers are poorly configured to address. The significant costs of designing infrastructure to allow for adaptation to long-term climate change impacts in the face of resource constraints, the tendency of transportation planners and engineers to extrapolate from the past and adopt incremental solutions when approaching new problems, and the lack of relevant information and guidance on which to base appropriate actions also affect how transportation planners and engineers view climate change.

A change in perspective is needed. First, transportation professionals must recognize climate change as a credible and important problem so that champions will emerge to bring attention to the issue and to make collaboration with climate scientists and meteorologists a priority. Second, addressing climate change requires a longer-term perspective and recognition that investment decisions made today, particularly about the location of transportation infrastructure, help shape long-term development patterns and markets well beyond the 30-year time frames of many public-sector capital improvement plans and private-sector capital budgeting analyses. These decisions also affect how well the transportation system will adapt to climate change in the near and long terms. Third, the significant costs of redesigning, retrofitting, and potentially having to relocate (or protect at great expense) some transportation infrastructure to adapt to potential impacts of climate change suggest the need for more strategic, risk-based approaches to decision making and infrastructure design. Such approaches should be better oriented to assessing the trade-offs between the costs of investments to make the infrastructure more robust and the likelihood and costs of facility failures or major disruptions to the system. The results of such assessments should be presented in a form that can be communicated to senior management and elected officials as a prudent action program, and provision should be made for adjustments as new knowledge becomes available. Finally, addressing the impacts of climate change that require regional and multistate responses is likely to entail developing new coalitions and organizational arrangements. Many of these changes will take time. Fortunately, transportation professionals have many avenues through which to begin to develop adaptation strategies, the topic of the next chapter.

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Abbreviations

IPCC	Intergovernmental Panel on Climate Change
UNEP	United Nations Environment Programme

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ANNEX 4-1

Applying Probabilistic Risk Assessment to Climate Change and Transportation

Probabilistic risk assessment (PRA) is a comprehensive, well-developed methodology for evaluating risks so they can be prioritized and managed more effectively. Properly applied, PRA will likely prove an indispensable tool for transportation managers considering the potential impacts of climate change.

CLASSIC RISK ASSESSMENT

The central idea behind PRA is to define risk as the product of the magnitude of adverse consequences and the probability that those consequences will occur. For instance, the risk of the loss of a coastal road due to a storm surge would be the likelihood of a storm surge rising high enough to inundate the road, multiplied by both the dollar cost of replacing the flooded road and the costs of the economic disruption during the time the road was unusable.

In principle, transportation managers could use this risk definition to thoroughly assess the risks posed by climate change for their system. They could list the full range of hazards associated with climate change for their region (e.g., sea level rise, heat) and then estimate the consequences that each hazard, if it occurred, would have for each transportation asset in their region. Each component of this equation has an associated probability. Thus, for example, there is a certain annual probability of occurrence for a 5-foot, 10-foot, or 20-foot storm surge; a certain probability that a road would fail if confronted by a 5-foot, 10-foot, or 20-foot storm surge; and a certain probability that the economic costs of such a failure would be $1 million, $5 million, or $10 million.

In sum, the risk due to climate change for all the assets in a manager's system would be given by

$$\text{Total risk} = \sum_{\substack{\text{all assets,}\\ \text{all hazards}}} \text{Prob(hazard)} \times \text{Prob(consequence)}$$

where the first term represents the probability densities for each hazard and the second term represents the probability densities for the costs of each hazard (including the probability and the cost of failure) for each asset in the transportation system.

Carrying out this analysis would provide transportation managers with an estimate of their total risk and the most important sources of that risk. (In practice, the probability of hazard is time dependent, and any future consequences for long-lived infrastructure would be discounted. However, this simplified expression is sufficient for the discussion below.) Note that the same contribution to risk can be made by a hazard with a relatively high probability of occurrence but moderate consequences and a hazard with a relatively low probability of occurrence but relatively high consequences. Such information provides a solid foundation for determining the most effective ways to manage the risk.

CHALLENGES OF ASSESSING THE RISKS OF CLIMATE CHANGE FOR TRANSPORTATION ASSETS AND SYSTEMS

In practice, it is difficult to carry out this calculation in its complete form. First, all the necessary data on the likelihood of the various hazards and their economic consequences may not be available. Second, significant uncertainty may be associated with the data that are available. Decision and risk analysts often distinguish between risk and uncertainty. In the former, knowledge of future events can be well characterized by probability distributions. In the latter, decision makers may not view the best available probability distributions as very reliable. For instance, if transportation managers were completely confident that the climate is not changing, they might have high confidence in estimates of the probability of moderate-probability hazards, that is, those expected to occur every 10 years or less as gleaned from weather records for their region extending back several decades or more. Managers might regard estimates of low-probability hazards, that is, those expected to occur every century, as less reliable. However, transportation managers have little basis for assuming that estimates of future climate-related hazards gleaned from past weather records in their region can serve as good estimates of the future likelihood of such events. They need to adjust their expectations on the basis of the results of probabilistic projections from climate models. As discussed in Chapter 2, some hazard estimates from such models, in particular, estimates of the likelihood of extreme events, may be less reliable than others.

The final reason that a comprehensive probabilistic risk assessment would prove difficult is that many transportation assets are long-lived, many of the most important impacts of climate change are expected to increase over time, and future transportation managers may take steps that can reduce (or perhaps unintentionally increase) the consequences of future climate changes. To address such changes over time, those who study the impacts of climate change identify four key factors that characterize the ability of a system to adjust to climate change. Using a slightly different language drawn from the ecological and biological literatures as opposed to the engineering literature of formal probabilistic risk assessment, the Intergovernmental Panel on Climate Change defines these factors as follows:

- Exposure, defined as the manner and degree to which a system is exposed to significant climate variations;
- Vulnerability, defined as the potential for loss, or the degree to which a system is susceptible to or unable to cope with adverse effects of climate change;
- Resilience, which refers to the restorative or regenerative capacity of a system when faced with change; and
- Adaptation, defined as the adjustment made to a system in response to actual or expected climate change to mitigate harm or exploit beneficial opportunities.

Exposure and vulnerability are similar to hazards and consequences. System-level resilience is a particularly important concept in the transportation sector because individual assets function as components of a network. The consequences of damage to any one asset will depend on the ability of traffic to reroute by using other routes or modes. They will also depend on the speed with which the affected private transportation providers and public agencies (e.g., state and local governments) can react and bring resources to bear to restore damaged systems to service. The resilience, or lack thereof, of the system can thus reduce or increase the consequences of damage to individual assets in the system.

Adaptation will also be an important component of transportation managers' ability to manage future risks associated with climate change. Managers today do not need to address the full range of potential impacts of future climate change because they can reasonably assume that future managers will take prudent steps to reduce the vulnerability of their assets and increase the resilience of their systems. However, some decisions made today can have implications that might make adaptation actions by future managers significantly more or less effective. For instance, some choices regarding the design and location of new transportation infrastructure may make it easier and less costly for future managers to adapt to climate changes if those changes turn out to be larger than currently expected. If there are two otherwise similar locations for a new road, for example, locating it farther from the coast will make it less costly for future managers to address any vulnerabilities of the asset should sea level rise turn out to be larger than currently expected.

CLIMATE RISK ASSESSMENT FOR TRANSPORTATION MANAGERS IN PRACTICE

The above factors—lack of complete data, uncertainty about the reliability of projections of future climate change, and uncertainty about the actions future managers will take to reduce the vulnerability and increase the resilience of a transportation system—make it difficult to conduct a comprehensive probabilistic risk analysis for a regional transportation system. In future years, more comprehensive planning frameworks can be expected to come into use that will help transportation managers integrate consideration of exposure, vulnerability, resilience, and adaptation factors. In the near term, however, a number of convenient and relatively simple methods can facilitate transportation managers' incorporation of these risk assessment concepts into their planning.

For instance, the California Seismic Retrofit Program (see Box 4-1) provides an example of a simple screening analysis, based on the concepts of probabilistic risk analysis, that allowed the California Department of Transportation to prioritize seismic retrofit investments for approximately 25,000 bridges on state and local highways. The screening criteria focused on both the vulnerability of individual assets and the resilience of the system. For instance, the program prescribed a higher performance standard for 11 major toll bridges, such as the San Francisco–Oakland Bay Bridge, whose loss would cause major economic disruption and whose replacement would be extremely expensive.

Transportation planners can address the potential for future system adaptation by time windows. For instance, operational decisions will be focused on near-term changes in weather and climate conditions, such as more frequent and more extreme events (e.g., intense precipitation and flooding), with which transportation operators are already familiar. Retrofit decisions will determine the performance of assets for several decades and thus should use probabilistic climate forecasts that extend out for several decades to estimate hazards. Finally, land use and location decisions for new infrastructure may influence transportation systems for a century or more, so managers should use probabilistic climate projections for future climate conditions extending into the 22nd century. The decision framework described in Box 4-2 provides one way to incorporate such considerations.

ROBUSTNESS AND SENSITIVITY ANALYSIS

Particularly when they use multidecadal and century-scale climate projections, transportation managers should pay heed to potentially significant uncertainties in these estimates. In particular, when transportation managers use probabilistic risk assessments to compare alternative design choices or even when they conduct a screening analysis, they should be aware of choices or rankings that are especially sensitive to particular probabilistic estimates. Engineers commonly incorporate safety factors into designs or design standards to account for unforeseen events or abnormal forces on structures. Similarly, transportation managers should recognize that it may be difficult for climate change projections to distinguish a future 100-year storm from a future 500-year storm, or that estimates of the likelihood that sea level rise will exceed 1 m by 2100 may change significantly in the years ahead. To the extent that they can make location decisions and design choices that account for such uncertainties in their risk assessments, today's transportation managers will help future stewards of their systems minimize avoidable surprises.

5

Meeting the Challenges

Adaptation to climate change would be necessary even if drastic mitigation measures were taken immediately to stabilize or even eliminate greenhouse gas (GHG) emissions (IPCC 2007). The effects of such global climate changes as warming temperatures and sea level rise occurring today reflect emissions of GHGs released into the atmosphere over the past century. Because of these long-lasting effects, the actions taken by transportation professionals today have implications for how the transportation system will respond to climate change in the near and long terms.

The first section of this chapter is organized on the basis of timescales that transportation decision makers must consider in determining how best to adapt to climate change. In the short term (i.e., the next several decades), transportation professionals are likely to have operational responses to changing climate conditions and climate extremes. Operators of transportation systems already react to many climate changes, particularly extreme events (e.g., intense precipitation, intense tropical storms) and can rapidly adapt operating and maintenance practices for those climate conditions projected to increase in frequency or intensity.

Rehabilitating or retrofitting infrastructure requires a longer time horizon because engineers design many infrastructure facilities with long service lives in mind (see Chapter 4), thereby providing fewer opportunities for adapting to changing climate conditions without incurring significant costs. Adapting facilities for climate change may also involve the reevaluation and development of design standards—a process that typically entails a lengthy research and testing program.

Finally, constructing new transportation infrastructure or providing major additions to existing transportation systems requires the longest time horizon. Transportation systems shape land use and development patterns, and in turn, population growth and economic development stimulate demand for new infrastructure facilities to support growth. In both cases, decisions made today about where to locate or expand transportation infrastructure establish development patterns that persist for generations and are difficult to change. These decisions should be weighed carefully to ensure that people and businesses are not placed in harm's way as projected climate changes unfold.

Following discussion of these topics, the chapter turns to many crosscutting issues—flood insurance; monitoring technologies and new materials; data, models, and decision support tools; and new partnerships and organizational arrangements—that can help facilitate adaptation to climate change or bring climate change issues into the decision-making process. The chapter ends with the committee's findings.

ADAPTATION STRATEGIES

Annexes 5-1A through 5-1C summarize a wide range of adaptation measures that can be used to address many of the climate change impacts discussed in Chapter 3 (see Annex 3-1). Potential adaptations are identified for land, marine, and air transportation, respectively, by response category: (*a*) changes in operations, (*b*) changes in infrastructure design and materials, and (*c*) other. No attempt is made to estimate the relative costs or effectiveness of these measures, although such analyses would be necessary to evaluate specific infrastructure investment alternatives. The remainder of this section addresses the key issues and opportunities for adaptation in each response category.

Operational Responses

The most rapid response to the impacts of climate change is likely to come through changes in transportation operating and maintenance practices.[1] Every U.S. transportation provider already experiences the adverse impacts of weather on operations under a diverse range of climate conditions. For example, approximately 75 percent of air travel delays in the National Airspace System are weather related (L. Maurice and M. Gupta, presentation to the committee, Jan. 4, 2007). Slick pavement and adverse weather

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[1] This section draws heavily on the paper by Lockwood (2006) commissioned for this study.

contribute to nearly one-quarter of all highway crashes and about 7,400 fatalities annually.[2] In addition, snow, ice, rain, and fog cause about 15 percent of total delays on the nation's highways (FHWA 2004; NRC 2004b). Weather also causes delays and interruptions in service for railroad and marine transportation.[3]

Transportation agencies expend considerable resources to address these conditions. For example, snow and ice control accounts for about 40 percent of annual highway operating budgets in snowbelt states (FHWA 2006a). Hurricane response is a major focus of transportation operations in states bordering the Gulf Coast. Collaboration between departments of transportation (DOTs) and emergency response personnel has improved, particularly in those areas of the country subject to recurring natural disasters—the Gulf Coast (hurricanes) and California (earthquakes and wildfires)—but still has a long way to go. Climate change is altering the frequency, intensity, and incidence of weather events.

Changes in Frequency of Extreme Weather Events

With changes in the frequency of extreme weather events, operational responses treated today on an ad hoc, emergency basis are likely to become part of mainstream operations. One could imagine, for example, that if strong (Category 4 and 5) hurricanes increased in frequency as is likely, widespread establishment of evacuation routes and use of contraflow operations[4] in affected areas might become as commonplace as snow emergency routes in the Northeast and Midwest. Mainstreaming such responses will require expanding the scope of the traditional operating focus of DOTs on traffic and incident management to include weather management, as well as improved training for operating personnel.

Increases in Intensity of Weather Events

Climate change is expected to trigger more extreme weather events, such as more intense precipitation, which are likely to produce areawide emergen-

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[2] Based on averages from 1995–2004 data collected by the National Highway Traffic Safety Administration and analyzed by Mitretek Systems.

[3] See, for example, Changnon (2006) on the impacts of weather and climate on American railroading and a report by the Office of the Federal Coordinator for Meteorological Services and Supporting Research on the impacts of weather on surface transportation modes (OFCM 2002).

[4] Contraflow involves the reversal of traffic flow on one or more of the inbound lanes and shoulders of roads and highways for use in the outbound direction to increase evacuation capacity in an emergency by using both sides of a roadway.

cies and may require evacuation of areas vulnerable to flooding and storm surge. In the wake of September 11, 2001, and Hurricanes Katrina and Rita, the U.S. Department of Homeland Security has mandated an all-hazards approach to emergency planning and response and encouraged better evacuation planning (DHS 2006). Coordination among state and local emergency managers—the first responders in an emergency—has improved, and emergency operations centers (EOCs) have been established in many metropolitan areas as command posts that can be activated rapidly in an emergency. Typically, transportation is a support function, but the critical role it plays in emergency response and especially in evacuation—a role that is likely to become more important as the climate changes—should be strengthened through increased collaboration between emergency managers and transportation providers and more representation of transportation agencies and private transportation providers at EOCs. Operators of transportation systems also need to work more closely with weather forecasters and emergency response planners to convey their own lead-time requirements for providing the necessary personnel and equipment in an evacuation and protecting their own assets. Finally, a greater emphasis on emergency management as a separate functional responsibility within DOTs and other transportation providers is needed.

Regional transportation management centers (TMCs) provide one location through which collaboration between transportation providers and emergency managers can occur (see Box 5-1). TMCs are currently focused on traffic monitoring and incident management through rapid deployment of police, fire and rescue, and emergency medical services. In some metropolitan areas, new functions are being added, such as better weather information and greater use of real-time traffic advisories, as well as links with emergency managers. Some TMCs are also serving as EOCs. However, integration of weather and emergency management functions in TMCs is still in its infancy according to a recent U.S. Department of Transportation assessment (FHWA 2006b).

Changes in Incidence of Weather Patterns

Climate changes will bring new weather patterns to previously unaffected areas of the United States. These changes, however, may not necessarily require the development of new operating and maintenance strategies. The United States has a diverse climate, ranging from subtropical to arctic

Box 5-1

Transportation Management Centers

Improving the efficiency of the existing highway network involves the application of technologies, such as intelligent transportation systems (ITS), and control strategies, such as ramp metering, dynamic message signs, and incident management. In many large metropolitan areas, these developments have been accompanied by establishment of regional transportation management centers (TMCs), which are seen as the cockpit or nerve center for monitoring traffic incidents and providing rapid police response, crash clearance, and travel advisories. Many TMCs are manned by staff from multiple agencies and jurisdictions working as a team.

Some TMCs are focused primarily on traffic and incident management. Others, such as Houston TranStar, have a broader scope. Opened in 1996, Houston TranStar is a consortium partnership of transportation and emergency management agencies in the greater Houston area housing engineers, law enforcement personnel, information technology specialists, and emergency managers. In addition to traffic monitoring and incident control, emergency management personnel from the Harris County Office of Emergency Management monitor potential emergencies due to severe weather using state-of-the-art technology, such as flood warning monitors, Doppler radar, satellite imagery, and weather data from the National Weather Service, to provide the public with real-time information.

The city of Chicago recently opened a new City Incident Center (CIC), which integrates the city's homeland security efforts with traffic services, among other activities. CIC follows on the creation of a Traffic Management Authority in 2005, dedicated to improving traffic flow through ITS technology and centralized control systems. The new facility will have positions dedicated to traffic management but will also provide a central location for communication among dispatch operators from all the relevant city departments so they can respond rapidly and effectively in the event of an emergency (*Inside ITS* 2006).

and from arid to wet, with several regions being subject to temperature extremes and such events as blizzards, hurricanes, tornadoes, floods, wildfires, avalanches, and mudslides. As climate patterns change, the transfer of best practices from one location to another will be essential. A mechanism is needed to encourage such information exchange, involving all transportation modes. This effort should build on existing technology transfer mechanisms, such as the Technology Implementation Group of the American Association of State Highway and Transportation Officials (AASHTO).[5]

Design Strategies

Operational responses are geared to addressing near-term impacts of climate change. To make decisions today about rehabilitating or retrofitting transportation facilities, especially those with long design lives (see Table 4-2 in the previous chapter), transportation planners and engineers must consider how climate changes will affect these facilities 50 years or more from now. Adapting to climate change will also require reevaluation, development, and regular updating of design standards that guide infrastructure design.

The purpose of design standards is to provide engineers with guidance on how to construct infrastructure for safe and reliable performance.[6] These standards represent the uniform application of the best engineering knowledge, developed through years of experimental study and actual experience. Often they become embedded in regulatory requirements and funding programs.[7] Design standards embody trade-offs between performance (e.g., safety, reliability) and cost. Faced with a myriad of factors that can affect performance, engineers typically select the most demanding parameter—the 100-year storm, the heaviest truck, the most powerful wind speed—as the basis for design, thereby building in a safety margin to minimize the chances of failure.

Environmental factors are integral to the design of transportation infrastructure. Conditions such as temperature, freeze–thaw cycles, and duration and intensity of precipitation determine subsurface and founda-

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[5] The primary objective of AASHTO's Technology Implementation Group, which grew out of an AASHTO task force's successful effort to implement products of the Strategic Highway Research Program, is to provide leadership to state DOTs, local governments, and industry in the selection and promotion of ready-to-implement technologies.

[6] This section draws heavily on the paper by Meyer (2006) commissioned for this study.

[7] To be eligible for federal funding, for example, state and local governments must comply with federal standards with respect to lane and shoulder widths on highways and bridge clearances over navigable waterways. If the infrastructure is damaged or destroyed, federal agencies and insurers typically allow renovation or rebuilding only to replacement standards; upgrading is not a reimbursable cost.

tion designs, choices of materials, and drainage capacity. The issue is whether current design standards are adequate to accommodate the climate changes projected by scientists. Table 5-1 provides an assessment by Meyer (2006) of the principal climate-induced changes and their implications for infrastructure design in both the short and long terms. Looking across all climate changes, the author notes that the most dominant impact is on those design elements most associated with forces resulting from water flows. This finding is not surprising in view of the extensive damage to transportation infrastructure and buildings caused by flooding and storm surge in Hurricanes Katrina and Rita. Climate changes, however, will not affect the design of all infrastructure modes equally, a second important observation. For example, wave action is more critical than temperature changes for coastal bridge design. Finally, climate extremes, such as stronger wind speeds, increased storm surges, and greater wave heights, will place the greatest demands on infrastructure because they are likely to push the limits of the performance range for which facilities were designed.

How should engineering design decisions be modified to address climate change, particularly for longer-lived infrastructure for which the uncertainties are greater regarding the magnitude and timing of climate changes? One option is to build to a more robust standard, assuming a greater frequency and magnitude of extreme events, without a full understanding of future risks and presumably at greater cost. This strategy could be appropriate for major facilities in vulnerable locations (e.g., critical bridges and evacuation routes), but its high costs necessitate a highly selective approach. Another option is to upgrade parallel routes, but this alternative depends on the availability of right-of-way and the cost of upgrading. A third option is to build infrastructure with shorter design lives, presumably at lower cost, to be retrofitted as more knowledge about future climate conditions is gained. This alternative probably is not viable in the United States because of the disruption and negative public reaction resulting from more frequent retrofits of major facilities. Most states are adopting a “fast in, fast out, and stay out” approach to major reconstruction projects. A final option is to hedge by building to current standards or making marginal improvements, recognizing that the infrastructure remains at risk and may require major improvements in the future. This alternative poses many of the same problems as the previous one. All four options involve important cost–risk reduction trade-offs that engineers

TABLE 5-1 **Climate-Induced Changes That Could Influence Transportation Infrastructure Design**

Climate-Change Phenomenon	Changes in Environmental Condition	Design Implications
Temperature change	Rising maximum temperature; lower minimum temperature; wider temperature range; possible significant impact on permafrost	Over the short term,[a] minimal impact on pavement or structural design; potential significant impact on road, bridge scour, and culvert design in cold regions Over the long term, possible significant impact on pavement and structural design; need for new materials and better maintenance strategies
Changing precipitation levels	Worst-case scenario, more precipitation; higher water tables; greater levels of flooding; higher moisture content in soils	Over the short term, could affect pavement and drainage design; need for greater attention to foundation conditions, more probabilistic approaches to design floods, more targeted maintenance Over the long term, definite impact on foundation design and design of drainage systems and culverts; impact on design of pavement subgrade and materials
Wind loads	Stronger wind speeds and thus loads on bridge structures; more turbulence	Over the short term, design factors for design wind speed might change; wind tunnel testing will have to consider more turbulent wind conditions Over the long term, need for materials of greater strength; impact on design considerations for suspended and cable-stayed bridges
Sea level rise	Rising water levels in coastal areas and rivers; increases in severe coastal flooding	Over the long term, greater inundation of coastal areas; need for more stringent design standards for flooding and building in saturated soils; greater protection of infrastructure needed when higher sea levels combine with storm surges
Greater storm surges and wave heights	Larger and more frequent storm surges; more powerful wave action	Over the short term, need for design changes to bridge height in vulnerable areas; need for more probabilistic approach to predicting storm surges Over the long term, need for changes to bridge design, both superstructure and foundations; changes in materials specifications; and more protective strategies for critical components

[a] For purposes of this table, short term is defined as the next 30 to 40 years; long term is from 40 to 100 years.

Source: Meyer 2006, Table 1.

and planners can best address through a more strategic, risk-based approach to design and investment decisions, such as that described in the previous chapter. The approach taken by Transit New Zealand to determine the necessity and feasibility of taking action now to protect the state highway network from the potential future impacts of climate change could also be instructive (see Box 5-2).

More fundamentally, the scientific community and professional associations must reevaluate design standards for transportation infrastructure that take climate change into account and begin the lengthy process of developing new standards where appropriate. Reexamination of design standards can be prompted by a single event, such as the damage to coastal highway bridges from Hurricane Katrina, when it became evident that the current state of practice—designing bridges for a riverine environment and a 50-year storm—was inadequate. The Federal Highway Administration (FHWA) not only approved and shared in the cost of rebuilding the damaged bridges to a higher design standard but also recommended the development of more appropriate bridge design standards in general for a coastal environment that would take into account the combined effects of storm surge and wave action and assume a more severe storm event (e.g., a 100-year or even 500-year storm) (FHWA 2005a).[8]

Typically, however, the development of design standards follows a time-consuming and systematic process that involves professional organizations in an extensive research and testing program over a period of decades. Once the standards are in place, engineers are understandably reluctant to change them. A combination of the length of time required to modify or develop new standards, the institutional procedures for approval of standards (vetting any changes through professional committees of practicing engineers), and the use of well-established standards as evidence of "good practice" in litigation leads to a conservative approach to change. Developing standards to address climate change in a timely manner thus will require leadership by the scientific community and professional associations and, given the scope of potential impacts, a broad-based, federally sponsored research program that must begin soon. A good model is the congressionally mandated National Earthquake

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[8] AASHTO and state DOTs are leading this initiative, and research on wave forces and wave load design practices is now being undertaken by universities and the U.S. Department of Transportation's Turner–Fairbank Highway Research Center, among others.

Box 5-2

Climate Change and Asset Management: New Zealand Transit's Approach to Addressing Impacts of Climate Change

Under the 2004 Resource Management (Energy and Climate Change) Amendment Act—New Zealand's principal legislation for environmental management—Transit New Zealand was required to take into account the effects of climate change as it plans, constructs, and maintains the state highway network (Kinsella and McGuire 2005). The key climate changes of concern to state highways are sea level rise, coastal storm surges, and increased frequency and intensity of heavy rainfall events. The primary assets at risk are bridges, culverts, causeways and coastal roads, pavement surfaces, surface drainage, and hillside slopes.

Transit New Zealand proceeded with a two-stage assessment to identify those areas requiring action. Stage 1 involved assessing the need to act now to manage future potential impacts of climate change. Three criteria were used:

- Level of certainty that the climate change impact will occur at the magnitude predicted in the specified time frame,
- Intended design life of the state highway asset, and
- Capacity of the agency's current asset management practice to manage the impact.

The results of the Stage 1 assessment revealed that current asset management practice is generally adequate to deal with impacts of climate change for most of the network, but that bridges and culverts with an intended design life of more than 25 years may require case-by-case consideration to ensure protection (Kinsella and McGuire 2005).

Stage 2 involved assessing the economic feasibility of acting now to manage future potential impacts of climate change and was focused on bridges and culverts with design lives of greater than 25 years. Making several simplifying assumptions, the analysis examined three options: (*a*) doing nothing, (*b*) retrofitting all existing bridges and culverts now to avoid future climate change impacts, and (*c*) designing all new bridges and culverts to accommodate future climate changes to 2080. The analysis revealed that it would not be economical to retrofit the existing stock of bridges and culverts, but it

(continued)

Box 5-2 (continued)

Climate Change and Asset Management: New Zealand Transit's Approach to Addressing Impacts of Climate Change

would be preferable to repair the assets when a specific loss or need became evident. The primary reasons for this conclusion were uncertainties about where and when the impacts of climate change will manifest themselves and the historical number of bridges and culverts lost prematurely because of other events. Retrofitting all new bridges and culverts to take climate change into account was also determined not to be economical. Nevertheless, the agency decided that, where possible, provision should be made for subsequent retrofitting (either lifting or lengthening the bridge) in the event impacts are experienced. For major bridges (and culverts) where retrofitting is not practical, the structure should be designed for projected future impacts of climate change on the basis of the best available information (Kinsella and McGuire 2005).

Transit New Zealand has amended its *Bridge Manual* to include consideration of relevant impacts of climate change as a design factor. In addition, the agency will continue to monitor climate change data and developments and review its policy when appropriate.

Hazard Reduction Program, begun in 1977, which has provided much of the underlying research for seismic standards (see Box 5-3).

New Infrastructure Investment, Transportation Planning, and Controls on Land Use

One of the most effective strategies for reducing the risks of climate change is to avoid placing people and infrastructure in vulnerable locations, such as coastal areas. Chapter 3 described the continuing development pressures on coastal counties despite the increased risk of flooding and damage from storm surge and wave action accompanying projected rising sea levels. Many areas along the Atlantic, Gulf, and Pacific coasts will be affected. Once in place, settlement patterns and supporting infrastructure are difficult to change. In New York City, for example, a major concern of emergency planners is handling the evacuation of some 2.3 million New Yorkers from flood-prone areas in the event of a Category 3 or greater hurricane (New York City Transit 2007). Continued development of such vulnerable areas

Box 5-3

Development of Seismic Standards in the United States

In 1977 Congress passed the Earthquake Hazards Reduction Act, which established the National Earthquake Hazard Reduction Program (NEHRP)—a long-term earthquake risk reduction program. Member agencies include the United States Geological Survey, the National Science Foundation, the Federal Emergency Management Agency, and the National Institute of Standards and Technology—agencies engaged primarily in research and development. The mission of NEHRP is broad and includes understanding the science of earthquakes and their effects, improving earthquake hazard identification and risk assessment methods, and developing effective practices (e.g., model building codes) and policies to reduce earthquake losses (NEHRP 2007).

One of the primary accomplishments of NEHRP has been the development of design standards for the seismic safety of buildings, both new and existing, which serve as a basis for national model building codes. Seismic standards and guidelines have also been developed for lifelines—telecommunications, transportation, water, sewage, electric power, gas, and liquid fuel lines. Adoption of the standards is voluntary, but some states, such as California, have incorporated the model national codes into state regulations, and the federal government has adopted the standards for its own buildings and as a prerequisite for obtaining federal funds. FHWA, for example, requires that federally assisted bridge and highway projects meet minimum seismic standards.

The development of seismic specifications for bridges began in the 1970s with the San Fernando earthquake and was spurred by the occurrence of subsequent major earthquakes. For example, the 1989 Loma Prieta earthquake led the American Association of State Highway and Transportation Officials to adopt a standard seismic specification for bridges in 1990. In response to the limitations of a "one-size-fits-all" approach, a modified performance-based standard was proposed in 1997, but it was rejected as being too complex and having too high a return frequency (2,500 years) relative to other hazards (Buckle 2006). (A performance-based national consensus standard has been developed for buildings.) Nevertheless, revisions are under way, and the performance-based approach, which takes into account different performance requirements and levels of risk, could be a model for the development of standards to address the impacts of climate change. A program such as NEHRP would be essential to fund the necessary supporting research and testing.

will only place more communities and businesses at risk and increase the difficulty of evacuation in the event of a major storm.

Why do transportation planners fail to consider development patterns in making investment decisions? The short answer is that they do, but not from the perspective of land use control. Public-sector transportation planners typically forecast expected land use patterns over a 25- to 30-year period as the basis for modeling future travel demand and infrastructure investment needs (Meyer and Miller 2001). However, they rarely consider whether such investments are desirable, or what development may result from building or expanding transportation networks (Amekudzi and Meyer 2005).[9] Although the long-term capital improvement and budgeting process is different in the private sector (see Chapter 4), it suffers from the same limitations. One of the main reasons for the disconnect between transportation investment decisions and land use and development decisions can be traced to governance arrangements. Decisions concerning large-scale transportation infrastructure investments are the responsibility of states, regional authorities, and the private sector. Local governments and a few states (e.g., Florida, California) control land use decisions through comprehensive plans, zoning ordinances, permitting, and building codes. Locally controlled land use planning, the typical situation in the United States, has too limited a perspective to account for the broadly shared risks of climate change. Local governments are interested primarily in the jobs and economic development that growth may bring to their communities, although in many localities, the costs of uncontrolled growth in terms of crowded roads and schools are being recognized. In some locations, greater integration of transportation and land use planning is resulting from smart growth policies, which recognize the impact of transportation investments on regional development and economic growth and vice versa; such integration is not common, however.

Transportation planners cannot resolve these issues single-handedly. The developers of any strategy that involves imposing land use controls to address climate change would need to build consensus among key decision makers in both transportation and land use, probably at the regional level—a challenging proposition. Nevertheless, if transportation planners

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[9] Meyer (2006) notes two locations—Lake Tahoe, Nevada, and Cape Cod, Massachusetts—where transportation planners have identified environmentally sensitive areas that are off limits to new infrastructure and development, but these are the exceptions rather than the rule.

were required to work more closely with land use planners and consider potential impacts of climate change in the development of long-term investment plans, the issues would become more visible.

At present, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) encourages greater collaboration and partnership among transportation planners and state and local agencies responsible for land use management, among others, in plan development.[10] In the reauthorization of this legislation, such collaboration should be required, as should consideration of climate change impacts and their effects on infrastructure plans and investments, particularly in vulnerable locations.

At the local level, some metropolitan planning organizations (MPOs) have already begun to adopt more flexible, scenario-based approaches in developing their long-range transportation investment plans (see Box 5-4). The impetus has come in part from the desire to provide local communities with a framework within which to better understand the impacts of growth and the difficult trade-offs among social, economic, and environmental goals in planning future transportation investments. Use of geographic information systems and modeling has enabled planners to illustrate and quantify the impacts of a range of regional growth scenarios on land use and area traffic, among other factors. At the end of the planning process, one scenario typically is selected as the preferred option. Development and monitoring of performance measures enable local planners to examine the effects of their choices and revisit the plans periodically to take into account new developments and changes in local priorities.

Scenario planning could be adapted to take potential climate changes into account in the development of future regional transportation plans. For example, projections of current development patterns and supporting transportation infrastructure, when overlaid on maps showing current elevations and expected sea level rise, could illustrate the increased risks of allowing uncontrolled development in vulnerable coastal areas and the desirability of managed growth policies and protection of critical infrastructure. Climate scientists, perhaps at local universities, could assist in the

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[10] More specifically, Section 6001 and the Final Rule on Statewide and Metropolitan Transportation Planning (*Federal Register* 2007) require that long-range transportation plans be developed in consultation with agencies responsible for land use management, natural resources, environmental protection, conservation, and historic preservation, and that state conservation plans or maps and inventories of natural or historic resources be consulted.

Box 5-4

Scenario Analysis in Transportation Planning

Scenario analysis as practiced by transportation planners is a process through which public agencies, private entities, and citizens work together to envision the long-term future of their communities (FHWA 2005b). Scenario planning starts with a business-as-usual baseline scenario, incorporating current plans or trends for a region. Then, a range of alternative future scenarios is identified on the basis of community input, through the use of tools and transportation models incorporating geographic information to identify impacts both quantitatively and visually. Typically, one scenario is chosen as the preferred alternative and is adopted as the region's vision for the future.

According to a recent survey, MPOs are the lead sponsors of scenario planning, followed by nonprofit organizations (e.g., environmental groups) and local governments (Bartholomew 2005). Numerous localities—Salt Lake City, Houston, Sacramento, Portland, Los Angeles, and Chicago, among others—have adopted this approach.

The recently released *2035 Regional Transportation Plan for Greater Houston* is a good example of the use of scenarios to examine the impacts of different land development choices on travel congestion, transit use, and population growth in floodplains and hurricane evacuation zones (Houston–Galveston Area Council 2007). Facing a projected 75 percent increase in population and a 60 percent increase in employment over the next 30 years, the council of governments for the greater Houston area—the Houston–Galveston Area Council—spearheaded the Envision Houston Region initiative in 2005 to engage elected officials, residents, and other stakeholders in planning and creating a long-term growth strategy to 2035. Four scenarios were considered, ranging from the status quo to a scenario assuming high-density mixed-use development along transit corridors and town centers; the latter is the selected Envision scenario, which planners believe offers a reasonable path forward and has considerable community support.

The regional plan also is notable for taking the first steps toward integrating climate change into the transportation planning process. The planners noted the vulnerability of the region to tropical storms and flooding, likely to be intensified by climate change and land subsidence, and the scenarios considered compared population growth in sensitive floodplains and hurricane evacuation areas. The chosen Envision scenario showed a reduction in population in both areas, alleviating demand on evacuation routes as compared with the baseline, status quo scenario.

planning process by identifying plausible impact scenarios. University of Washington climate scientists, for example, developed projections of sea level rise for Seattle that became a consideration in designing a major rehabilitation of the Alaskan Way Seawall.[11]

In those major metropolitan areas highly vulnerable to the impacts of climate change, where projected sea level rise combined with storm surge could threaten already densely developed areas—parts of New York City, Miami, and San Francisco, for example—options such as levees and storm barrier systems are likely to be considered to protect valuable real estate. These options are costly, they can create environmental problems, and they may provide a false sense of security.[12] Moreover, as was the experience in New Orleans, levees can encourage development in "protected" flood risk areas (ASFPM 2007). In small communities, exposure to impacts of climate change may necessitate abandoning homes, businesses, and infrastructure and relocating inland. For example, reduced sea ice along Alaska's Arctic coast is already eroding shoreline and exposing coastal areas to the action of winter storm surges and waves, a pattern that will be exacerbated by further sea level rise. Some 200 Native American villages are at risk and may soon be abandoned for inland locations (ACIA 2004).

CROSSCUTTING ISSUES

Flood Insurance

Private insurers may be able to accomplish what government cannot in terms of land use control. Some major insurers, for example, are refusing to write new or renew existing homeowners' policies in areas already vulnerable to hurricanes and other severe storms, which are likely to intensify in a warming climate (Adams 2006). Florida, Texas, Louisiana, Mississippi, Hawaii, New York City, and Long Island are among the affected areas thus

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[11] Sea level projections from the climate impacts research group at the University of Washington suggested that the city's current design standards for the new seawall did not adequately account for the potential projected rise in sea level. Given the magnitude of the long-term financial and transportation impacts of the Alaskan Way Seawall project, the City Auditor's Office recommended that the city obtain a comprehensive, independent analysis that would consider all available scientific sources in estimating the probabilities of expected increases in sea level and their rate (Soo Hoo and Sumitani 2005).

[12] Levees interfere with the natural attenuation of flows from floodwaters, cause backwaters, generally increase the depth and velocity of floodwaters, and encourage channel degradation and eventual bank erosion (ASFPM 2007).

far. Some states, such as Florida, have stepped up to become insurers of last resort for coastal homes and businesses, but the high costs of providing coverage are unlikely to be sustainable or would result in prohibitive premium increases in many cases if the costs were passed on to homeowners. Moreover, the provision of insurance in hazard-prone areas that is not actuarially sound is bad public policy.

The federal government is already the insurer of last resort for homeowners and businesses that cannot secure affordable private flood insurance in flood hazard areas. In 1968 Congress authorized the National Flood Insurance Program (NFIP) to mitigate increasing taxpayer-funded flood relief. The Federal Emergency Management Agency (FEMA) administers the program and maps the nation's floodplains; these maps serve as the basis for determining the eligibility of homeowners and businesses for NFIP funding. To become eligible, a community must adopt and enforce floodplain management ordinances and building code requirements to reduce future flood damage.[13] In exchange, NFIP makes federally backed, affordable flood insurance available to homeowners, renters, and businesses in mapped Special Flood Hazard Areas (SFHAs) through licensed agents and insurance companies. Flood insurance is required to secure financing for buying, building, or improving a structure in SFHAs. New buildings must be elevated to or above the predicted 100-year flood level, and foundations must be designed to resist flood loads (Elliott 2005). Buildings that are repaired or improved after floods must be brought into compliance with these ordinances if the repair costs 50 percent or more of the market value of the structure.

Over the years, NFIP has been criticized for encouraging more development in these flood-prone areas than would have occurred without the program (Elliott 2005; Burby 2006). Others suggest that the program has had little impact because many properties (e.g., beach houses) are purchased without a mortgage and thus need not comply with floodplain ordinances. Communities have also been slow to enact and enforce floodplain management measures. Finally, flood insurance is not required of properties located behind levees that have been certified for 100-year storms, even though such properties are at enhanced risk for any flood that exceeds the 100-year storm. Because climate change is projected to

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[13] Details of the program were accessed from the FEMA website at www.fema.gov/about/programs/nfip.shtm on May 9, 2007.

trigger more intense storms and sea level rise will extend the areas of flood damage in some SFHAs, FEMA and congressional oversight committees should reevaluate the risk reduction effectiveness of the program.

FEMA is engaged in a multiyear map modernization program to provide reliable digital flood hazard data and maps in support of NFIP. However, the maps are based on historical data and thus do not take account of climate change. The SFHA boundaries are keyed to the 100-year storm, the base elevation data are inadequate (NRC 2007), and the pace of updating is slow. In fact, some states have taken over the task of updating to speed up the process. Further additions to flood zone maps may be needed and are particularly important to transportation engineers because these maps have become a quasi–design standard for determining appropriate drainage capacity, for example, for transportation infrastructure in coastal areas.

Monitoring Technologies and New Materials

Better monitoring technologies and new materials could offer engineers alternatives to costly infrastructure retrofit or replacement in advance of climate change. For example, better systems for monitoring impacts of climate change on infrastructure could provide engineers with an early warning of problems, buying time for making the necessary modifications. This approach would also provide a good solution for less critical infrastructure facilities for which the costs of retrofitting in anticipation of climate change are not economical. In Alaska, where climate warming is occurring more rapidly than in the lower 48 states, engineers are closely monitoring bridge foundations for scour. Hotter, dryer summers have led to increased glacial melting and longer periods of high stream flows, leading to both increased sediment transport on rivers and scour at bridge crossings. A network of sonars has been installed on several scour-critical bridges around the state. The monitoring data are sent regularly to the Alaska Department of Transportation and Public Facilities (J. Conaway, United States Geological Survey, personal communication, March 8, 2006), an approach that could be adapted for use in other states.[14]

Sensors and other “smart” technologies yet to be developed could also be used more widely to monitor changing climate conditions and issue

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[14] The FHWA scour program requires bridge owners to evaluate bridges for potential scour associated with the 100-year storm and a 500-year superflood event (FHWA 2005a).

warnings when thresholds are exceeded. Sensors are already available that monitor changing pressures on a building or bridge and issue a warning when the pressures become abnormal (Meyer 2006). Sensors could also be embedded in pavements and bridge decks, for example, to monitor stress and strain as temperatures change, enabling remedial action to be taken before failure occurs. The collapse of the Minneapolis Interstate 35W bridge in August 2007 brought renewed attention to the need for better technologies to monitor bridge conditions. Numerous technologies are available: X-ray machines can spot hidden cracks in girders, computerized monitors can track minute changes in stresses on steel beams, and sensors embedded in concrete can track corrosion of steel reinforcing beams. The costs are not small—one estimate to install monitoring equipment on a large bridge was $250,000—but relative to retrofitting or replacing a failed structure, the costs are marginal (*Inside ITS* 2007). Advances in material sciences (applications of nanotechnologies),[15] computer processing, and communications capabilities, as well as in sensor technologies, could provide a fertile field for the development of devices for monitoring climate changes and communicating the results to the appropriate infrastructure owners.

New materials also hold promise for addressing some climate changes. For example, temperature extremes, particularly increases in very hot days and heat waves, are likely to affect both pavements and rails. Changnon et al. (1996) report that highways and railroads were damaged by heat-induced heaving and buckling of joints during the 1995 heat wave in Chicago. Extreme heat can also cause misalignment of rail lines and derailments, although the use of continuous welded rail should prevent kinks from occurring (Changnon 2006). Continued research and development of materials that can withstand high temperatures would be productive, as would effective mechanisms for sharing new knowledge.

Data, Models, and Decision Support Tools

Data systems for monitoring the impacts of climate change can be an effective tool for determining appropriate adaptation strategies. One such system is the Alaska Engineering Design Information System (AEDIS), described in Chapter 3. AEDIS provides geographic-specific data on tem-

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[15] Nanotechnology is a field of applied science focused on control of matter on a scale smaller than 1 micrometer, normally 1 to 100 nanometers, as well as the fabrication of devices on this same scale.

peratures, precipitation levels, permafrost, and snow depth collected from weather stations located around the state. The data are intended to help in deriving engineering design parameters (e.g., load-bearing capacity), scheduling maintenance and repairs, and selecting optimum locations for transportation infrastructure (T. Douglas, Cold Regions Research and Engineering Laboratory, personal communication, March 9, 2006). As trend data accumulate, AEDIS could provide a useful repository of information on the longer-term impacts of climate change on infrastructure that could be linked with a database of response strategies and costs—from changes in maintenance practices, to use of new materials, to design changes.

Improving information on weather for transportation infrastructure applications is another important area for development, particularly in view of the potential for more climate extremes. The national needs assessment report of the Weather Information for Surface Transportation initiative (OFCM 2002)—a joint effort of the National Oceanic and Atmospheric Administration (NOAA) and FHWA—identifies as a particular need more accurate information at higher spatial (e.g., surface temperatures) and temporal resolutions (OFCM 2002). The information must also be provided with sufficient lead time (for forecasts) and currency (for observations) to guide operational decisions. Providing the data will require improved weather detection and forecasting; better understanding of thresholds for precipitation, temperature, winds, and the like, which affect transportation operations and, if exceeded, could cause significant interruptions in operations or infrastructure failure; and improvements in data integration and real-time communication to both transportation operators and system users (Lockwood 2006). Clarus, a major initiative of FHWA's Surface Transportation Weather Program,[16] is already working to develop and demonstrate an integrated nationwide surface weather observing, forecasting, and data management system. A range of observational technologies, from remote to fixed sensors to vehicle probes, are being tested as sources of real-time data, as is a suite of tools to make use of the data. Such efforts could have application for other transportation modes.

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[16] The Surface Transportation Weather Program was authorized in SAFETEA-LU for $5 million annually for 4 years. The primary focus is on alleviating the impacts of adverse weather on the safety and reliability of the nation's highways.

The 2004 and 2005 hurricane seasons provided a vivid illustration of the need for improvements in modeling of the effects of storm surge and wave action, which will be aggravated by sea level rise. NOAA's Sea, Lake, and Overland Surge from Hurricanes model and, more recently, the Advanced Circulation Model (ADCIRC) (described in Chapter 2) have been used to estimate the threat from storm surge.[17] These models use historical input data that are infrequently updated. For example, when ADCIRC was run with input data through the 2005 hurricane season, it was found that the magnitude of the 100-year storm-surge flood would now reoccur at an interval of 75 years. After Hurricane Katrina, considerable research was also conducted on wave action on bridges (J. Krolak, briefing, Wave Force Symposium, Turner–Fairbank Highway Research Center, July 27, 2006); the results of this research should help in revising coastal bridge design standards.

If extreme weather events require evacuation of affected areas, better modeling to support evacuation efforts will be needed. Some MPOs are using travel demand models to estimate the time required to evacuate regional areas for different types of emergencies, but this is not common practice. For example, according to modeling estimates provided after Hurricane Rita by the Houston–Galveston Area Council, the council of governments for the Houston metropolitan area, it would take 80 to 120 hours to evacuate 3 million residents from Galveston, Houston, and other coastal areas, assuming use of contraflow and optimum flow conditions. The necessary lead time far exceeds the ability of meteorologists to predict the landfall and trajectory of hurricanes (Houston–Galveston Area Council 2007), and this has led local governments to consider hardening public facilities on higher ground and encouraging residents in nonvulnerable coastal areas to shelter in place. Simulation models are also being used to help identify optimal evacuation routes, compute estimated evacuation times, and determine traffic management needs for an emergency planning area (Goldblatt and Weinisch 2005). However, these models must be upgraded to provide more real-time information to assist emergency man-

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[17] ADCIRC is being applied in southern Louisiana by the U.S. Army Corps of Engineers New Orleans District to design levee heights and alignments, by FEMA to establish flooding probabilities for insurance purposes, by the State of Louisiana at the Center for the Study of Public Health Impacts of Hurricanes to operationally predict hurricane inundation, and by the Louisiana State Department of Natural Resources to assess coastal restoration projects (information from the ADCIRC website, accessed at www.adcirc.org on October 10, 2007).

agers and transportation providers in responding to an incident (e.g., by changing routing instructions and notifying emergency response teams).

New Partnerships and Organizational Arrangements

Adapting successfully to climate change will require forging new partnerships and organizational arrangements that better align with the impacts of climate change, which do not follow modal, jurisdictional, or corporate boundaries. As discussed earlier, decision making in the transportation sector is structured around these boundaries. Transportation planning is conducted primarily at the regional level, often in a bottom-up process that starts with local jurisdictions. Railroads, trucking, and waterborne commerce are largely private enterprises with varying levels of federal participation.

Partnerships could involve closer collaboration between transportation agencies and emergency responders. Tabletop exercises, for example, in which emergency managers and critical transportation agencies, among others, role play their responses to hypothetical emergency situations (e.g., a terrorist attack, a major hurricane), provide an opportunity for such coordination and contact. Other relevant partnerships could involve local collaboration between university climate scientists and regional transportation planners; greater interaction between transportation planners and those who control land use (both described previously); and creation of a more formal process for better communication among transportation professionals, climate scientists, and other relevant scientific disciplines, along with a repository for transportation-relevant climate change information.

The creation of regional and multistate organizational arrangements to address climate change is a formidable challenge but could yield enormous payoffs in the ability to respond not only to climate change but also to other natural and man-made disasters (e.g., earthquakes, terrorist incidents). The transportation sector has some models for cross-jurisdictional arrangements, such as regional authorities for specific facilities (e.g., the Alameda Corridor in California).[18] Regional and multistate emergency

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[18] Created as a Joint Powers Authority by affected cities, the Ports of Los Angeles and Long Beach, and the Los Angeles County Metropolitan Transportation Authority, the Alameda Corridor Transportation Authority guided the development of a 20-mile-long rail cargo expressway. The expressway separates freight rail from street traffic and passenger trains while linking the ports to the transcontinental rail network near downtown Los Angeles.

response operations that include transportation are beginning to emerge in the wake of hurricanes and other disasters, such as the events of September 11, 2001. These might serve as the nucleus for multistate regional compacts to address other issues, such as the impacts of climate change (Deen 2006). State-mandated regional compacts for addressing regional air quality issues offer another model.[19] One could imagine the emergence of similar arrangements to address such problems as the impact of sea level rise on coastal real estate and infrastructure in the tristate New York area or other coastal areas, the effects of drought on shipping along inland waterways, or the impact of hurricanes in the Gulf Coast region.

The development of organizational arrangements "right-sized" to address the problems for transportation infrastructure created by climate change may require state or federal action. The California Coastal Commission is a good example of a state initiative designed to resolve a regional problem. In the early 1970s, many Californians became alarmed that private development was cutting off public access to the shore and by voter initiative petitioned the state to exert its stewardship role to protect coastal assets for future generations. In 1976 the state legislature enacted the California Coastal Act and established a permanent California Coastal Commission, which plans and regulates development and use of natural resources along the coast in partnership with local governments and in keeping with the requirements of the Coastal Act (California Coastal Commission 2007). One could imagine a similar arrangement to mediate land use and development issues in vulnerable coastal areas in light of projected climate changes.

FINDINGS

Adaptation is unavoidable to address the impacts of climate change due to GHG emissions released into the atmosphere decades ago or longer. The prudent strategy is for transportation professionals to begin now to take a

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[19] In the eastern half of the United States, for example, where regional ozone is an important concern, organizations such as the Ozone Transport Commission and the ad hoc Ozone Transport Assessment Group were established, the former in 1991 under the auspices of the federal Clean Air Act Amendments. In the west, where degrading visibility in scenic areas is a growing problem, the Grand Canyon Visibility Transport Commission and its successor, the Western Regional Air Partnership, were established as voluntary organizations representing western states, tribes, and the federal government. The main purpose of these groups is to recommend and implement multistate mitigation strategies for air pollution that extend beyond any one state border (NRC 2004a).

more proactive approach in addressing both past and potential future impacts of climate change. A wide array of adaptation options is available.

The most immediate response is likely to come through changes in transportation operating and maintenance practices. These changes will involve incorporating responses to more extreme weather events into routine operations, improving collaboration with emergency managers, recognizing weather and emergency management as integral functions of transportation agency operations, and widely sharing best practices. To make decisions about rehabilitating or retrofitting transportation infrastructure with long service lives, transportation planners and engineers will need to consider how climate change will affect these facilities 50 years or more into the future. Design changes may also be required to harden long-lived infrastructure in locations particularly vulnerable to climate changes. The development of new standards to address climate change will be a time-consuming process, requiring research and testing and the consensus of practicing engineers. In view of the myriad of potential climate change impacts to be considered, the scientific community and relevant professional organizations should take the lead in initiating a program soon, with federal support for the necessary research and testing. Relocation of some transportation systems, such as coastal roads and rail lines, may ultimately prove necessary. Costly levees or storm barrier systems may be considered to protect valuable real estate in selected densely populated exposed areas.

One of the most effective strategies for reducing the risks of climate change is to avoid placing people and infrastructure in vulnerable locations. This is not always possible in highly developed areas, but more stringent land use controls and flood insurance requirements could help curb further development. Federal planning regulations should require that transportation planners take climate change into account in developing long-range plans, as well as collaborate with agencies responsible for land use, so that the consequences of infrastructure investment decisions for land use and vice versa can be more clearly identified. FEMA should reevaluate the risk reduction effectiveness of NFIP. At a minimum, updating of flood zone maps to account for sea level rise (incorporating land subsidence) should be a priority in coastal areas.

Better monitoring technologies and new materials could also provide alternatives to costly upgrading of some infrastructure. More widespread use of sensors for monitoring impacts of climate change and new heat-resistant paving materials are examples. More refined data (e.g., better elevation data for floodplain mapping, more accurate data on surface temperatures) and improved modeling—from weather forecasting to modeling of expected storm surge and real-time evacuation scenarios—are needed as well.

Adapting to climate change will also require new partnerships and organizational arrangements that better align with climate impacts than do current modal, jurisdictional, and corporate boundaries around which decision making in the transportation sector is structured. Some models for regional and multistate cooperation exist in regional emergency response initiatives and in regional authorities and compacts for air quality, but state or federal incentives may be necessary to ensure the development of organizations "right-sized" to address the problems for transportation infrastructure raised by climate change.

At the federal level, an interagency working group could be created, focused solely on adaptation issues for the transportation sector, to help shape existing agency research programs. The U.S. Department of Transportation would be the natural lead for this activity.

Embracing these adaptation strategies would require overcoming many of the barriers outlined in Chapter 4. First and foremost, transportation leaders would need to agree that climate change is a problem that warrants action. Thinking longer term, adopting more risk-based approaches to investment decisions, and forging new partnerships and organizational arrangements are among the greatest challenges. The next and final chapter provides the committee's recommendations for moving forward.

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Abbreviations

ACIA	Arctic Climate Impact Assessment
ASFPM	Association of State Floodplain Managers
DHS	U.S. Department of Homeland Security
FHWA	Federal Highway Administration
IPCC	Intergovernmental Panel on Climate Change
NEHRP	National Earthquake Hazards Reduction Program
NRC	National Research Council
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research

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ANNEX 5-1A **Potential Climate Changes, Impacts on Land Transportation, and Adaptation Options**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Temperature: increases in very hot days and heat waves	Limitations on periods of construction activity due to health and safety concerns; restrictions typically begin at 29.5°C (85°F); heat exhaustion possible at 40.5°C (105°F) Vehicle overheating and tire deterioration	Impacts on pavement and concrete construction practices Thermal expansion on bridge expansion joints and paved surfaces Impacts on landscaping in highway and street rights-of-way Concerns regarding pavement integrity, e.g., softening, traffic-related rutting, migration of liquid asphalt; sustained air temperature over 32°C (90°F) is a significant threshold Rail-track deformities; air temperature above 43°C (110°F) can lead to equipment failure	Shifting construction schedules to cooler parts of the day	Development of new, heat-resistant paving materials Greater use of heat-tolerant street and highway landscaping Greater use of continuous welded rail lines	

(continued)

ANNEX 5-1A *(continued)* **Potential Climate Changes, Impacts on Land Transportation, and Adaptation Options**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Temperature: decreases in very cold days	Regional changes in snow and ice removal costs and environmental impacts from salt and chemical use (reduction overall, but increases in some regions) Fewer cold-related restrictions for maintenance workers	Decreased utility of unimproved roads that rely on frozen ground for passage	Reduction in snow and ice removal Extension of construction and maintenance season Shortening of season for use of ice roads		
Temperature: increases in Arctic temperatures		Thawing of permafrost, causing subsidence of roads, rail beds, bridge supports (cave-in), and pipelines Shorter season for ice roads	Shortening of season for use of ice roads Lengthening of potential construction season Increased use of sonars to monitor streambed flow and bridge scour	Use of insulation in the road prism Use of different types of passive refrigeration schemes, including thermosiphons, rock galleries, and "cold culverts"	Relocation of sections of roads and rail lines to more stable ground

Temperature: later onset of seasonal freeze and earlier onset of seasonal thaw	Changes in seasonal weight restrictions Changes in seasonal fuel requirements Improved mobility and safety associated with a reduction in winter weather Longer construction season	Reduced pavement deterioration resulting from less exposure to freezing, snow, and ice, but possibility of more freeze–thaw conditions in some locations	Relaxation of seasonal weight restrictions Shortening of season for use of ice roads		
Sea level rise, added to storm surge	More frequent interruptions in travel on coastal and low-lying roadways and rail service due to storm surges More severe storm surges, requiring evacuation	Inundation of roads and rail lines in coastal areas More frequent or severe flooding of underground tunnels and low-lying infrastructure Erosion of road base and bridge supports Bridge scour Reduced clearance under bridges Loss of coastal wetlands and barrier shoreline Land subsidence		Elevation of streets, bridges, and rail lines Addition of drainage canals near coastal roads Elevation and protection of bridge, tunnel, and transit entrances Additional pumping capacity for tunnels	Relocation of sections of roads and rail lines inland Protection of high-value coastal real estate with levees, seawalls, and dikes Strengthening and heightening of existing levees, seawalls, and dikes Restriction of most vulnerable coastal areas from further development Increase in flood insurance rates to help restrict development

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ANNEX 5-1A *(continued)* **Potential Climate Changes, Impacts on Land Transportation, and Adaptation Options**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
					Return of some coastal areas to nature
Precipitation: increase in intense precipitation events	Increases in weather-related delays Increases in traffic disruptions Increased flooding of evacuation routes Disruption of construction activities Changes in rain, snowfall, and seasonal flooding that affect safety and maintenance operations	Increases in flooding of roadways, rail lines, and subterranean tunnels Overloading of drainage systems, causing backups and street flooding Increases in road scouring, road washout, damages to railbed support structures, and landslides and mudslides that damage roadways and tracks Impacts on soil moisture levels, affecting structural integrity of roads, bridges, and tunnels	Expansion of systems for monitoring scour of bridge piers and abutments Increase in monitoring of land slopes and drainage systems Increases in monitoring of pipelines for exposure, shifting, and scour in shallow waters Increases in real-time monitoring of flood levels Integration of emergency evacuation procedures into operations	Protection of critical evacuation routes Upgrading of road drainage systems Protection of bridge piers and abutments with riprap Increases in culvert capacity Increases in pumping capacity for tunnels Addition of slope retention structures and retaining facilities for landslides Increases in the standard for drainage capacity for new	Greater use of sensors for monitoring water flows Restriction of development in floodplains

		Adverse impacts of standing water on road bases Increases in scouring of pipeline roadbeds and damages to pipelines		transportation infrastructure and major rehabilitation projects (e.g., assuming a 500-year rather than a 100-year storm)	
Precipitation: increases in drought conditions for some regions	Increased susceptibility to wildfires, causing road closures due to fire threat or reduced visibility	Increased susceptibility to wildfires that threaten transportation infrastructure directly Increased susceptibility to mudslides in areas deforested by wildfires	Vegetation management		
Precipitation: changes in seasonal precipitation and river flow patterns	Benefits for safety and reduced interruptions if frozen precipitation shifts to rainfall, depending on terrain	Increased risk of floods from runoff, landslides, slope failures, and damage to roads if precipitation changes from snow to rain in winter and spring thaws			
Storms: more frequent strong hurricanes (Category 4–5)	More debris on roads and rail lines, interrupting travel and shipping More frequent and potentially more extensive emergency evacuations	Greater probability of infrastructure failures Increased threat to stability of bridge decks Increased damage to signs, lighting fixtures and supports	Emergency evacuation procedures that become more routine Improvements in ability to forecast landfall and trajectory of hurricanes	Changes in bridge design to tie decks more securely to substructure and strengthen foundations	Strengthening and heightening of levees Restriction of further development in vulnerable coastal locations

(continued)

ANNEX 5-1A *(continued)* **Potential Climate Changes, Impacts on Land Transportation, and Adaptation Options**

	Impacts on Land Transportation (Highways, Rail, Pipeline)		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
		Decreased expected lifetime of highways exposed to storm surge	Improvements in monitoring of road conditions and issuance of real-time messages to motorists Improvements in modeling of emergency evacuation	Increases in drainage capacity for new transportation infrastructure or major rehabilitation projects (e.g., assuming more frequent return periods) Removal of traffic bottlenecks on critical evacuation routes and building of more system redundancy Adoption of modular construction techniques where infrastructure is in danger of failure Development of modular traffic features and road sign systems for easier replacement	Increase in flood insurance rates to help restrict development Return of some coastal areas to nature

ANNEX 5-1B **Potential Climate Changes, Impacts on Marine Transportation, and Adaptation Options**

	Impacts on Marine Transportation		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Temperature: increases in very hot days and heat waves	Impacts on shipping due to warmer water in rivers and lakes				
Temperature: decreases in very cold days	Less ice accumulation on vessels, decks, riggings, and docks; less ice fog; fewer ice jams in ports		Improvement in operating conditions from less ice accumulation, fog, and jams		
Temperature: increases in Arctic temperatures	Longer ocean transport season and more ice-free ports in northern regions Possible availability of a Northern Sea Route or a Northwest Passage		Longer ice-free shipping season and increased access to more ice-free ports and resources in remote areas Longer season for barge transport		

(continued)

ANNEX 5-1B *(continued)* **Potential Climate Changes, Impacts on Marine Transportation, and Adaptation Options**

	Impacts on Marine Transportation		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Temperature: later onset of seasonal freeze and earlier onset of seasonal thaw	Extended shipping season for inland waterways (especially the St. Lawrence Seaway and the Great Lakes) due to reduced ice coverage		Increases in summer load restrictions	Design of shallower-bottom vessels for seaway travel	More dredging, but environmental and institutional issues Shifts to other transportation modes
Sea level rise, added to storm surge	More severe storm surges, requiring evacuation	Changes in harbor and port facilities to accommodate higher tides and storm surges Reduced clearance under bridges Impacts on navigability of channels: some will be more accessible (and farther inland) because of deeper waters, while others will be restricted because of changes in sedimentation	More frequent bridge openings to handle shipping	Raising of dock and wharf levels and retrofitting of other facilities to provide adequate clearance Protection of terminal and warehouse entrances Elevation of bridges and other structures	More dredging of some channels Raising or construction of new jetties and seawalls to protect harbors

Precipitation: increase in intense precipitation events	Increases in weather-related delays	Impacts on harbor infrastructure from wave damage and storm surges Changes in underwater surface and silt and debris buildup can affect channel depth		Strengthening of harbor infrastructure to protect it from storm surge and wave damage Protection of terminal and warehouse entrances from flooding	More dredging on some shipping channels
Precipitation: increases in drought conditions for some regions	Impacts on river transportation routes and seasons		Restrictions on shipping due to channel depth along inland waterways and on other river travel		More dredging on some shipping channels and harbors Release of water from upstream sources Shifts to other transportation modes
Precipitation: changes in seasonal precipitation and river flow patterns	Periodic channel closings or restrictions if flooding increases Benefits for safety and reduced interruptions if frozen precipitation shifts to rainfall	Changes in silt deposition leading to reduced depth of some inland waterways and impacts on long-term viability of some inland navigation routes	Restrictions on shipping due to channel depth along inland waterways and on other river travel		More dredging on some shipping channels

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ANNEX 5-1B *(continued)* **Potential Climate Changes, Impacts on Marine Transportation, and Adaptation Options**

	Impacts on Marine Transportation		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Storms: more frequent strong hurricanes (Category 4–5)	Implications for emergency evacuation planning, facility maintenance, and safety management	Greater challenge to robustness of infrastructure Damage to harbor infrastructure from waves and storm surges Damage to cranes and other dock and terminal facilities	Emergency evacuation procedures that become more routine	Hardening of docks, wharves, and terminals to withstand storm surge and wave action	

ANNEX 5-1C **Potential Climate Changes, Impacts on Air Transportation, and Adaptation Options**

	Impacts on Aviation		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Temperature: increases in very hot days and heat waves	Delays due to excessive heat Impact on lift-off load limits at high-altitude or hot-weather airports with insufficient runway lengths, resulting in flight cancellations or limits on payload (i.e., weight restrictions), or both More energy consumption on the ground	Heat-related weathering and buckling of pavements and concrete facilities Heat-related weathering of vehicle stock	Increase in payload restrictions on aircraft at high-altitude or hot-weather airports Increase in flight cancellations	Development of new heat-resistant runway paving materials Extension of runway lengths at high-altitude or hot-weather airports, if feasible	
Temperature: decreases in very cold days	Changes in snow and ice removal costs and environmental impacts from salt and chemical use Reduction in need for deicing		Reduction in snow and ice removal Reduction in airplane deicing		

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ANNEX 5-1C *(continued)* **Potential Climate Changes, Impacts on Air Transportation, and Adaptation Options**

	Impacts on Aviation		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
	Fewer limitations on ground crew work at airports, typically restricted at wind chills below –29°C (–20°F)				
Temperature: increases in Arctic temperatures		Thawing of permafrost, undermining runway foundations		Development of new runway paving materials Major repair of some runways	Relocation of some landing strips
Temperature: later onset of seasonal freeze and earlier onset of seasonal thaw					
Sea level rise, added to storm surge	Potential for closure or restrictions for several of the top 50 airports that lie in	Inundation of airport runways located in coastal areas		Elevation of some runways	Construction or raising of protective dikes and levees

	coastal zones, affecting service to the highest-density populations in the United States				Relocation of some runways, if feasible
Precipitation: increase in intense precipitation events	Increases in delays due to convective weather Storm water runoff that exceeds the capacity of collection systems, causing flooding, delays, and airport closings Implications for emergency evacuation planning, facility maintenance, and safety management	Impacts on structural integrity of airport facilities Destruction or disabling of navigation aid instruments Runway and other infrastructure damage due to flooding Inadequate or damaged pavement drainage systems	More disruption and delays in air service More airport closures	Increases in drainage capacity and improvement of drainage systems supporting runways and other paved surfaces	
Precipitation: increases in drought conditions for some regions	Decreased visibility at airports located in drought-susceptible areas with potential for increased wildfires				

(continued)

ANNEX 5-1C *(continued)* **Potential Climate Changes, Impacts on Air Transportation, and Adaptation Options**

	Impacts on Aviation		Adaptation Options		
Potential Climate Change	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design and Materials	Other
Precipitation: changes in seasonal precipitation and river flow patterns	Benefits for safety and reduced interruptions if frozen precipitation shifts to rainfall	Inadequate or damaged pavement drainage systems		Increases in drainage capacity and improvement of drainage systems supporting runways and other paved surfaces	
Storms: more frequent strong hurricanes (Category 4–5)	More frequent interruptions in air service	Damage to landside facilities (e.g., terminals, navigation aids, fencing around perimeters, signs)		Hardening of terminals and other facilities	

6

Summing Up

The charge to this committee was to review the current scientific understanding of climate change from the perspective of those changes of particular relevance for U.S. transportation, including the limits of current knowledge; to identify potential impacts on U.S. transportation infrastructure and operations; to consider adaptation options; and to offer recommendations on actions that can be taken to prepare for climate change and on needed research. In this final chapter, the committee presents its consensus findings and recommendations in response to this charge, along with its principal supporting arguments. The committee's consensus position was informed by the five papers commissioned for this study; the 1-day conference held midway through the study to obtain the input of a broad range of transportation academicians and practitioners, climate scientists, and other experts; reviews of previous studies that examined the potential impacts of climate change on transportation, with a focus on adaptation strategies; numerous briefings on a wide range of relevant topics presented at committee meetings; and the committee's own expertise and judgment. The chapter is organized on the basis of a series of questions that guided the committee's thinking.

WHICH CLIMATE CHANGES ARE MOST RELEVANT FOR U.S. TRANSPORTATION?

> ***Finding:*** *The past several decades of historical regional climate patterns commonly used by transportation planners to guide their operations and investments may no longer be a reliable guide for future plans. In particular, future climate will include new classes (in terms of magnitude and frequency) of weather and climate*

> *extremes, such as record rainfall and record heat waves, not experienced in modern times as human-induced changes are superimposed on the climate's natural variability.*

Transportation planners and engineers typically extrapolate from historical weather and climate patterns in planning and designing infrastructure. The past will not be a good predictor of future conditions, however, as climate changes bring new weather patterns and climate extremes that exceed current experience. Projections of future climate are often depicted as gradual changes, such as the rise in global temperatures or in sea levels projected over this century. However, climate changes are unlikely to be experienced in such a smooth manner because human-induced changes will be amplified in some years by naturally fluctuating conditions, reflected in potentially sudden and dramatic changes at the regional or local level, where transportation infrastructure is located. Warming temperatures may trigger weather extremes and surprises, such as more rapid melting of the Arctic sea ice or more rapid rise in sea levels than is projected by current climate models.

On the basis of current knowledge, climate scientists have identified five climate changes of particular importance to U.S. transportation and estimated the probability of their occurrence during the 21st century:

- Increases in very hot days and heat waves (very likely),[1]
- Increases in Arctic temperatures (virtually certain),
- Rising sea levels (virtually certain),
- Increases in intense precipitation events (very likely), and
- Increases in hurricane intensity (likely).

HOW WILL CLIMATE CHANGE AFFECT U.S. TRANSPORTATION?

> ***Finding:*** *Climate change will affect transportation primarily through increases in several types of weather and climate extremes, such as very hot days; intense precipitation events; intense hurri-*

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[1] The Intergovernmental Panel on Climate Change (IPCC) (2007) Working Group I established the following terminology to describe uncertainty, that is, the probability of occurrence: virtually certain, >99 percent; extremely likely, >95 percent; very likely, >90 percent; likely, >66 percent; more likely than not, >50 percent; unlikely, <33 percent; very unlikely, <10 percent; extremely unlikely, <5 percent.

> *canes; drought; and rising sea levels, coupled with storm surges and land subsidence. The impacts will vary by mode of transportation and region of the country, but they will be widespread and costly in both human and economic terms and will require significant changes in the planning, design, construction, operation, and maintenance of transportation systems.*

Transportation infrastructure was designed for typical weather patterns and environmental conditions, reflecting local climate and incorporating assumptions about a reasonable range of temperatures and precipitation levels. It will be affected most by those climate changes that cause environmental conditions to extend outside the range for which the system was designed.

> ***Finding:*** *Potentially, the greatest impact of climate change for North America's transportation systems will be flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence.*

Fully 53 percent of the U.S. population now lives in counties with coastal regions, many among the most densely populated in the nation. If development pressures continue in vulnerable coastal areas, and there is every reason to believe they will, the impacts of climate change will be magnified as increasing numbers of people and businesses are placed in harm's way, and the infrastructure is expanded or new infrastructure is built to accommodate the growth. The Atlantic and Gulf Coasts are particularly vulnerable because they have already experienced high levels of erosion, land subsidence, and loss of wetlands. Their vulnerability to the storm surges and wave action that accompany strong tropical storms was amply demonstrated during the 2005 hurricane season. Sea level rise and coastal flooding also pose risks for the East Coast, as well as the Pacific Northwest and parts of the California coast.

The impacts of climate change will not be limited to coastal areas. For example, watersheds supplying water to the St. Lawrence Seaway and the Great Lakes, as well as the Upper Midwest river system, are likely to experience drier conditions, resulting in lower water levels and reduced capacity to ship agricultural and other bulk commodities, although a longer shipping season could offset some of the adverse economic effects. Thawing permafrost in Alaska is already creating settlement and land subsidence problems for roads, rail lines, runways, and pipelines. Higher temperature extremes (mainly heat waves) in some U.S. regions could lead to more frequent buckling of pavements and misalignment of rail lines. More severe weather events with intense precipitation could increase the severity of extensive flooding events, such as the storms that plagued the Midwest during the 1993 flooding of the Mississippi and Missouri River system, the Chicago area in 1996, and the Houston region during Tropical Storm Allison in 2001. Flooding of a waterway system can knock out barge operations on the river itself, rail operations on rights-of-way adjacent to the river, and even highway approaches to bridges crossing flooded rivers.

Not all climate change impacts will be negative. For example, the marine transportation sector could benefit from more open seas in the Arctic, creating new and shorter shipping routes and reducing transport time and costs. In cold regions, expected temperature rises, particularly decreases in very cold days and later onset of seasonal freezes and earlier onset of seasonal thaws, could mean reduced costs of snow and ice control for departments of transportation and safer travel conditions for passenger vehicles and freight.

> **Recommendation 1: Federal, state, and local governments, in collaboration with owners and operators of infrastructure, such as ports and airports, and private railroad and pipeline companies, should inventory critical transportation infrastructure in light of climate change projections to determine whether, when, and where projected climate changes in their regions might be consequential.**

Inventorying transportation assets essential to maintaining network performance to determine their potential vulnerability to projected climate changes is a sensible first step. Information about projected climate changes is currently available from climate scientists for large subcontinental regions—a scale more relevant than global projections for regional and local transportation infrastructure. Although such an inventory must be updated periodically as new scientific knowledge about climate change becomes available, inventorying is a relatively low-cost activity. Many of the tools needed for the purpose [e.g., geographic information systems (GIS)] are available. The inventorying process itself should help identify with greater precision the data needed on transportation-relevant climate changes and encourage collaboration between transportation professionals and climate scientists.

HOW SHOULD TRANSPORTATION DECISION MAKERS RESPOND?

> ***Finding:*** *Public authorities and officials at various governmental levels and executives of private companies are continually making short- and long-term investment decisions that have implications for how the transportation system will respond to climate change in the near and long terms.*

Transportation decision makers have an opportunity now to prepare for projected climate changes. Decisions made today, particularly those related to the redesign and retrofitting of existing or the location and design of new transportation infrastructure, will affect how well the system adapts to climate change far into the future. Many transportation facilities, such as bridges, large culverts, and rail and port facilities, are designed with long service lives and help shape development patterns that, once in place, are difficult to change. Thus, transportation planners and engineers should consider how projected climate changes in their regions might affect these facilities.

> **Recommendation 2: State and local governments and private infrastructure providers should incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans.**

Taking measures now to evaluate and protect the most vulnerable infrastructure should pay off by diminishing near-term maintenance expenditures and reducing the risk of catastrophic failure, with its toll on human life and disruption of economic activity. Such measures might include strengthening or elevating some coastal roads, rail lines, and bridges, particularly those that serve as evacuation routes, or upgrading parallel routes where they are available.[2] In the longer term, relocation of

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[2] States in particularly vulnerable regions such as the Gulf Coast could consider securing and banking rights-of-way for alternative evacuation routes, should they prove necessary.

rights-of-way farther inland or installation of costly storm barrier systems to protect selected areas (e.g., parts of New York City or Miami) might be considered.

> ***Finding:*** *The significant costs of redesigning and retrofitting transportation infrastructure to adapt to potential impacts of climate change suggest the need for more strategic, risk-based approaches to investment decisions.*

Designing transportation facilities to more robust standards to hedge against potentially negative impacts of climate change will produce much more costly designs that are likely to be unacceptable given limited budgets. More strategic and selective risk-based approaches are needed for determining appropriate design standards and investment priorities. Transportation professionals already take risk into account, particularly in designing facilities. For example, structures are designed to withstand certain wind speeds on the basis of probabilistic assessments of wind speed occurrence using historical data on wind speed frequency. Drainage requirements for many transportation facilities are sized to accommodate the 100-year storm, a probabilistic assessment of storm frequency. Engineers also commonly incorporate safety factors into designs or design standards to account for unforeseen events or abnormal forces on structures. In general, however, transportation decision makers have a long way to go to take full advantage of quantitative, risk-based approaches that incorporate uncertainty and probabilistic assessments in making investment and design decisions.

> **Recommendation 3: Transportation planners and engineers should use more probabilistic investment analyses and design approaches that incorporate techniques for trading off the costs of making the infrastructure more robust against the economic costs of failure. At a more general level, these techniques could also be used to communicate these trade-offs to policy makers who make investment decisions and authorize funding.**

At present, the necessary data and certitude about projections of future climate, particularly at the local and regional levels, are not available to permit a comprehensive probabilistic risk assessment and analysis. However, more simplified approaches can be used by transportation planners and engineers to incorporate many of these risk assessment concepts into their planning and design. One model is the California Seismic Retrofit Program. Following the Loma Prieta earthquake in 1989, the California Department of Transportation developed a risk-based approach for analyzing the vulnerability of highway bridges statewide to earthquakes and their criticality to the network to make it possible to determine investment priorities for retrofitting and replacement. The program established a higher performance standard for 750 structures to protect the investment in these major facilities and ensure that these vital transportation lifelines would remain in service after a major seismic event to provide access for emergency responders. The state's 11 major toll bridges were handled separately because their complexity demanded a time-consuming dynamic analysis. For most other bridges, the standard was "no collapse" under a maximum seismic event, consistent with the geographic location of the bridge. The objective was to avoid loss of life; however, some damage to a structure was acceptable as long as it remained intact and could be reopened for service soon after the event.

Extending and incorporating such techniques to include climate change will require more complete data on the likelihood of climate-related hazards and their economic consequences. It will also necessitate continuing education of current planners and engineers and training of future professionals. Finally, educating policy makers to gain their support will entail communicating the information so that the trade-offs and investment priorities are clear. It may also require new eligibility criteria in funding programs, and new funding sources may also be necessary to make the investments identified by the application of these techniques.

WHAT DATA AND DECISION SUPPORT TOOLS ARE NEEDED?

> ***Finding:*** *Transportation professionals often lack sufficiently detailed information about expected climate changes and their timing to take appropriate action.*

Transportation decision makers note that one of the most difficult aspects of addressing climate change is obtaining the relevant information in the form they need for planning and design. This difficulty is not limited to the transportation sector. A recent National Research Council report (NRC

2007) found that while the scientific understanding of climate change has made great progress, the use of that knowledge to support decision making and formulate mitigation and adaptation strategies is much less well developed. Climate change is understood with greatest confidence as a global or continental phenomenon, while transportation planners as well as other decision makers need local and regional climate projections. They also need a better understanding of how projected climate changes, such as changes in temperature and precipitation, will affect the environment (e.g., soil moisture, runoff) in which the infrastructure is situated, which will vary from region to region. Climate projections themselves are presented by climate scientists as a portfolio of plausible scenarios and outcomes, which are continually refined and revised as new knowledge accumulates. Transportation planners need to have a better understanding of which scenarios are most plausible for their regions and most significant for their operations and plans.

> **Recommendation 4: The National Oceanic and Atmospheric Administration, the U.S. Department of Transportation (USDOT), the U.S. Geological Survey, and other relevant agencies should work together to institute a process for better communication among transportation professionals, climate scientists, and other relevant scientific disciplines, and establish a clearinghouse for transportation-relevant climate change information.**

All professions should benefit from the collaboration. Transportation professionals would be encouraged to define with greater precision the climate data needed to improve transportation decisions, such as temperature and precipitation thresholds at finer-grained geographic scales or climate conditions that would create unacceptable performance outcomes. Climate scientists would be challenged to elaborate on the possibilities and limitations of projecting impacts of climate change at the levels of geographic specificity that are most useful for transportation planners. And hydrologists and others would be challenged to consider how the environment would influence these effects and their impacts on transportation infrastructure. One promising approach might be for the federal government to support a number of pilot projects in which federal agencies would work closely with local transportation planners to include the full range of relevant climate information that could affect a specific project.

> ***Finding:*** *Better decision support tools are also needed to assist transportation decision makers.*
>
> **Recommendation 5: Ongoing and planned research at federal and state agencies and universities that provide climate data and decision support tools should include the needs of transportation decision makers.**

For example, the research program of the USDOT Center for Climate Change and Environmental Forecasting could be charged with expanding its existing research program in this area and provided the necessary funding. Needed tools include accurate digital elevation maps in coastal areas for forecasting the effects of flooding and storm surge heights; GIS that can be used to map the locations of critical infrastructure, overlaid with information on climate change effects (e.g., sea level rise, permafrost melt); greater use of scenarios that include climate change in the development of long-range regional transportation plans to pinpoint likely vulnerabilities (e.g., areas susceptible to sea level rise, aggravated by storm surge) and ways to address them; and better transportation network models for examining the systemwide effects of the loss of critical transportation infrastructure links.

WHICH ADAPTATION STRATEGIES MAKE SENSE?

Transportation decision makers have a wide range of adaptation options from which to choose in determining how best to adjust to climate change. One way to organize these options is around the timescales used by transportation professionals in their decision making. For example, operational decisions are typically focused on the short term and thus will be concerned mainly with near-term changes in weather and climate conditions. Decisions about rehabilitating or retrofitting infrastructure are made with a longer time horizon in mind. Such decisions will determine the performance of those assets with long service lives for many decades and thus should take longer-term climate projections into consideration so likely hazards can be assessed. Decisions about new infrastructure or major capacity additions involve the longest time frame because they will shape land use and development patterns for years to come and thus may require consideration of climate change projections that extend into the 22nd century. Other adaptation options, such as monitoring and use of technology or new organizational arrangements, cut across timescales and offer adaptation options in their own right or ways to better incorporate climate change in transportation decision making.

Operational Responses

> ***Finding:*** *Projected increases in extreme weather and climate underscore the importance of emergency response plans in vulnerable locations and require that transportation providers work more closely with weather forecasters and emergency planners and assume a greater role in evacuation planning and emergency response.*

U.S. transportation providers already address the impacts of weather on transportation system operations in a diverse range of climatic conditions. For example, snow and ice control accounts for about 40 percent of annual highway operating budgets in the northern U.S. states. Likewise, hurricane planning has become a major focus of transportation operations in the Gulf Coast states, where transportation providers are forging close relationships with emergency responders to handle severe weather events.

As climate changes induce new extremes (e.g., more intense storms, more intense precipitation), operational responses are likely to become more routine and proactive than today's approach of treating severe weather on an ad hoc, emergency basis. For example, if hurricanes increase in intensity, as is likely to be the case, establishment of evacuation routes and use of contraflow operations may become as commonplace as the current use of snow emergency routes in the Northeast and Midwest. More accurate and timely weather prediction and communication of storm warnings in real time to those potentially in harm's way will become more important.

> **Recommendation 6: Transportation agencies and service providers should build on the experience in those locations where transportation is well integrated into emergency response and evacuation plans.**

Following the events of September 11, 2001, and the experience with Hurricanes Katrina and Rita, coordination between state and local emergency managers—the first responders in an emergency—and transportation agencies and service providers improved, particularly in those locations with recurring natural disasters, such as hurricanes. In some locations, transportation is represented at emergency operations centers—command posts that can be activated rapidly in an emergency. Transportation agencies and service providers are also working closely with weather forecasters and emergency response planners to convey their own lead-time requirements so they can provide the personnel and equipment necessary for evacuation and protect their own assets. Transportation agencies and service providers in locations where collaboration is not as advanced should build on this experience.

Monitoring and Use of Technology

> ***Finding:*** *Greater use of technology would enable infrastructure providers to monitor climate changes and receive advance warning of potential failures due to water levels and currents, wave action, winds, and temperatures exceeding what the infrastructure was designed to withstand.*

Monitoring infrastructure conditions, particularly the impacts of weather and climate extremes, offers an alternative to preventive retrofitting or reconstruction of some facilities. It is also an activity that can begin immediately. In Alaska, which is experiencing more accelerated climate changes than the lower 48 states, the Alyeska Pipeline Company already monitors the right-of-way of the Trans-Alaska Pipeline System to spot land subsidence problems, particularly along the 800 miles of pipeline elevated on vertical supports. Alaskan engineers also closely monitor bridge supports, which are experiencing damage from earlier winter runoff and increased stream flow. In the future, sensors and other "smart" technologies could be embedded in the infrastructure to monitor changing climate conditions and impacts and provide warning when pressure or stress thresholds are being exceeded. Development of more heat-resistant materials could help protect pavements and some rail facilities, in particular, from the adverse impacts of projected temperature extremes.

> **Recommendation 7: Federal and academic research programs should encourage the development and implementation of monitoring technologies that could provide advance warning of pending failures due to the effects of weather and climate extremes on major transportation facilities.**

Advances in sensor technologies, computer processing, and communications capabilities should provide a fertile field for the development of smart devices that can be used for monitoring changing climate conditions and communicating the results to the appropriate transportation infrastructure owners. Advances in material sciences should enable the development of new materials that can withstand climate extremes.

Sharing of Best Practices

> ***Finding:*** *The geographic extent of the United States—from Alaska to Florida and from Maine to Hawaii—and its diversity of weather and climate conditions can provide a laboratory for identifying best practices and sharing information as the climate changes.*

As a result of climate change, many areas of the United States will experience new climate-induced weather patterns. These changes, however, may not necessarily require the development of new operating and maintenance strategies. The United States has a diverse climate, ranging from subtropical to arctic and from arid to wet, with several regions being subject to temperature extremes and such events as blizzards, hurricanes, tornadoes, floods, wildfires, avalanches, and mudslides. As climate patterns change, transfer of best practices from one location to another will be essential.

> **Recommendation 8: The American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration, the Association of American Railroads, the American Public Transportation Association, the American Association of Port Authorities, the Airport Operators Council, associations for oil and gas pipelines, and other relevant transportation professional and research organizations should develop a mechanism to encourage sharing of best practices for addressing the potential impacts of climate change.**

This effort should build on technology transfer mechanisms that already exist, such as AASHTO's technology-sharing program. Technology should be defined broadly to include probabilistic decision-making tools, as well as monitoring technologies, new materials, and operating and maintenance strategies.

Design Changes

> ***Finding:*** *Reevaluating, developing, and regularly updating design standards for transportation infrastructure to address the impacts of climate change will require a broad-based research and testing program and a substantial implementation effort.*

Operational responses are geared to addressing near-term impacts of climate change, but rehabilitating or retrofitting transportation facilities—many of which are designed to have long service lives—requires that transportation planners and engineers consider how climate changes will affect the performance of these facilities 50 or more years into the future. Opportunities for adaptation are limited once a facility has been renovated unless engineers build in the potential to make subsequent changes. Addressing climate change will also require reevaluation, development, and regular updating of design standards that guide infrastructure design.

Environmental factors are integral to the design of transportation infrastructure. Conditions such as temperature, freeze–thaw cycles, and duration and intensity of precipitation determine subsurface and foundation designs, the choice of materials, and drainage capacity. Engineers, however, have given little thought to whether current design standards are adequate to accommodate climate change. For example, will drainage capacity be adequate for expected increases in intense precipitation events? Many infrastructure components are currently designed for the 100-year storm, but projections indicate that today's 100-year precipitation event is likely to occur every 50 or perhaps even every 20 years by the end of this century. What new materials and operating practices might be needed when very hot temperatures and heat waves become more frequent? Are infrastructure components sufficiently strong to withstand the forces of larger and more frequent storm surges and more powerful wave action, the effects of which were vividly demonstrated when Hurricane Katrina simply lifted bridge decks off their supporting structures?

Developing standards is a time-consuming consensus process that typically involves professional organizations in an extensive research and testing program. Changes in design practices tend to be incremental, and building to higher standards to strengthen transportation infrastructure so it can accommodate the adverse impacts of climate change must be weighed against the costs involved.

Recommendation 9: USDOT should take a leadership role, along with those professional organizations in the forefront of civil engineering practice across all modes, to initiate immediately a federally funded, multiagency research program for ongoing reevaluation of existing and development of new design standards as progress is made in understanding future climate conditions and the options available for addressing them. A research plan and cost proposal should be developed for submission to Congress for authorization and funding of this program.

Developing standards to address climate change in a timely manner requires leadership by the scientific community and professional associations and, given the scope of the potential impacts, a broadly based, federally sponsored research program. The initial focus of such a program should be on essential links in transportation networks, particularly those vulnerable to climate changes in coastal areas or in low-lying areas in riverside locations. A good model is the congressionally mandated National Earthquake Hazard Reduction Program, begun in 1977, which established a research effort and a coordination mechanism to reduce the risks to life and property from earthquakes through the development of standards that afford different levels of protection for different levels of risk. If a similar program is to be launched to address climate change in a timely manner, it should be initiated soon.

Recommendation 10: In the short term, state and federally funded transportation infrastructure rehabilitation projects in highly vulnerable locations should be rebuilt to higher standards, and greater attention should be paid to the provision of redundant power and communications systems to ensure rapid restoration of transportation services in the event of failure.

Following Hurricane Katrina, for example, the Federal Highway Administration recognized that current design standards for coastal highway bridges—which were based on a riverine environment and a 50-year storm—were inadequate. The agency approved and shared in the cost of rebuilding bridges damaged in the hurricane to a higher design standard, and it recommended the development of bridge design standards more appropriate for a coastal environment, which take into account the combined effects of storm surge and wave action and assume a more severe storm event (e.g., a 100-year or even a 500-year storm). AASHTO is leading the effort to develop a new consensus standard. Hurricane Katrina also showed the importance of power and communications systems to the restoration of transportation services (e.g., operation of traffic lights, rail signal systems, pumping stations, air traffic control facilities, and nighttime running lights).

> ***Finding:*** *Federal agencies have not focused generally on adaptation in addressing climate change.*

The development of appropriate design standards to accommodate climate change is only one of several possible adaptation strategies that may require federal leadership, research, and funding.

> **Recommendation 11: USDOT should take the lead in developing an interagency working group focused on adaptation.**

This initiative would not necessarily require new funding beyond that recommended above. Better collaboration among federal agencies could help focus attention on adaptation issues and shape existing research programs.

Transportation Planning and Land Use Controls

> ***Finding:*** *Transportation planners are not currently required to consider climate change impacts and their effects on infrastructure investments, particularly in vulnerable locations.*

One of the most effective strategies for reducing the risks of climate change is to avoid placing people and infrastructure in vulnerable locations. Transportation planners currently consider expected land use patterns when forecasting future travel demand and infrastructure needs. However, they rarely question whether such development is desirable, much less what effects climate change might have on the provision and development of infrastructure in vulnerable locations. In part, this situation stems from governance arrangements. States, regional authorities, and the private sector are responsible for large-scale transportation investment decisions, but local governments and a few states control land use decisions through comprehensive plans, zoning ordinances, permitting, and building codes. In some locations, transportation and land use planning are becoming more integrated as a result of smart growth policies, which recognize the impact of transportation investments on regional development and economic growth and vice versa; however, such integration is uncommon.

> **Recommendation 12: Federal planning regulations should require that climate change be included as a factor in the development of public-sector, long-range transportation plans; eliminate any perception that such plans should be limited to 20 to 30 years; and require collaboration in plan development with agencies responsible for land use, environmental protection, and natural resource management to foster more integrated transportation–land use decision making.**

Current surface transportation legislation encourages such collaboration. During reauthorization, requiring transportation planners to both consider climate change and collaborate with land use planners in the preparation of public-sector, long-range plans could go a long way toward making these issues more visible. Some metropolitan planning organizations are already using scenario-based approaches to illustrate the trade-offs among social, economic, and environmental goals and understand the impacts of different long-range investment plans. Scenario planning could be adapted to take potential climate changes into account, and the results could provide the basis for discussion with local governments and developers responsible for land use decisions, particularly in vulnerable areas.

> ***Finding:*** *Locally controlled land use planning, which is typical throughout the country, has too limited a perspective to account for the broadly shared risks of climate change.*

Any strategy that involves land use controls to address climate change would need to build consensus among key decision makers in transportation and land use, probably at the regional level—a challenging proposition. Federal and state incentives may be needed to encourage new organizational arrangements, a topic discussed later in this chapter.

Insurance

> ***Finding:*** *The National Flood Insurance Program and the flood insurance rate maps (FIRMs) that determine program eligibility do not take climate change into account.*

The federal government is the insurer of last resort for homeowners and businesses that cannot secure affordable private flood insurance in specially designated flood hazard areas. The National Flood Insurance Program, authorized by Congress in 1968 to mitigate increasing taxpayer-funded flood relief, is administered by the Federal Emergency Management Agency (FEMA). FEMA maps the nation's floodplains, and eligible homeowners and businesses receive below-cost insurance. In return, the local community must adopt and enforce floodplain management measures, including building code ordinances for new construction and rebuilding after a disaster, to reduce flood damage. In practice, critics contend that the program has resulted in more development than would otherwise have occurred in these areas. Moreover, the accuracy of the FIRMs used to determine program eligibility is woefully inadequate, despite a mapping modernization program. Flood hazard area boundaries are keyed to the 100-year storm, and base elevation data are inadequate. The maps are based on historical data and thus do not factor in such climate changes as sea level rise and storm surge.

> **Recommendation 13: FEMA should reevaluate the risk reduction effectiveness of the National Flood Insurance Program and the FIRMs, particularly in view of projected increases in intense precipitation and storms. At a minimum, updated flood zone maps that account for sea level rise (incorporating land subsidence) should be a priority in coastal areas.**

Climate change may trigger more intense storms, and sea level rise will extend the scope of flood damage in some special flood hazard areas. FEMA and congressional oversight committees should reevaluate the risk reduction effectiveness of the National Flood Insurance Program in light of these projected changes. The FIRMs should account for climate change and the likelihood that it will extend the boundaries of some special flood hazard areas, which are keyed to the 100-year storm. These changes are particularly important to transportation engineers because the FIRMs have become a quasi–design standard, for example, for determining appropriate drainage capacity for transportation infrastructure in coastal areas.

New Organizational Arrangements

> ***Finding:*** *Current institutional arrangements for transportation planning and operations were not organized to address climate change and may not be adequate for the purpose.*

The impacts of climate change do not follow modal, corporate, or jurisdictional boundaries, yet decision making in the transportation sector is structured around these boundaries. Transportation planning is conducted primarily at the regional level, often through a bottom-up process that starts with local jurisdictions. Railroads, trucking, and waterborne commerce are largely private enterprises with varying levels of federal participation. Thus, existing institutional arrangements are not well suited to addressing climate change. Some models of cross-jurisdictional cooperation exist, such as regional authorities for specific facilities (e.g., the Alameda Corridor); regional and multistate emergency response agreements; and state-mandated regional authorities, such as those responsible for air quality improvement. One could imagine the emergence of similar arrangements to address, for example, the impact of sea level rise on coastal real estate and infrastructure in the tristate New York area or other coastal areas, or the effects of drought on shipping along inland waterways, or the impact of hurricanes in the Gulf Coast region. However, state or federal incentives may be required to ensure the development of such organizational arrangements at the regional or multistate level.

> **Recommendation 14: Incentives incorporated in federal and state legislation should be considered as a means of addressing and mitigating the impacts of climate change through regional and multistate efforts.**

For example, states could use updated FIRMs or their own state maps to identify geographic areas vulnerable to climate change and craft policies for restricting transportation investments and limiting insurance in these locations.

WHAT ACTIONS AND RESEARCH ARE NEEDED TO PREPARE FOR CLIMATE CHANGE?

At the outset of this study, the committee was asked to provide recommendations on actions to be taken to prepare for climate change and on needed research. The committee interpreted this charge broadly, particularly as it applies to research. Many of its recommendations relate to the development and sharing of information, decision support tools, and new technologies and materials, as well as research more narrowly defined. The committee also attempted to identify who should implement each of its recommendations.

Actions to prepare for climate change can be taken almost immediately. The committee recommends that transportation agencies and service providers inventory critical infrastructure in light of climate change projections (Recommendation 1); incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans (Recommendation 2); incorporate more probabilistic investment analyses and design approaches and communicate the results of these analyses to policy makers in ways that highlight trade-offs and investment priorities (Recommendation 3); and build on the experience of locations where transportation is well integrated into emergency response and evacuation plans to prepare for projected weather and climate extremes (Recommendation 6).

Other steps depend on federal and state action. Federal planning regulations should require inclusion of climate change in the development of long-range plans and collaboration between transportation and land use agencies (Recommendation 12); state and federally funded transportation infrastructure rehabilitation projects in highly vulnerable locations should be rebuilt to higher standards until design standards can be assessed more broadly in light of climate change (Recommendation 10); FEMA should reevaluate the risk reduction effectiveness of the National Flood Insurance Program and update the FIRMs, both in light of climate change (Recommendation 13); and federal and state legislation should incorporate incentives to encourage the development of regional and multistate efforts to address the impacts of climate change (Recommendation 14).

Research needs, broadly defined, include establishing a process for better communication among transportation professionals, climate scientists, and other relevant scientific disciplines and a clearinghouse for transportation-relevant information on climate change (Recommendation 4); developing climate data and decision support tools that incorporate the needs of transportation decision makers (Recommendation 5); developing and implementing monitoring technologies for major transportation facilities to provide advance warning of pending failures due to severe weather events and climate extremes (Recommendation 7); developing a mechanism for sharing best practices to address potential impacts of climate change (Recommendation 8); initiating a federally funded, multiagency research program for reevaluation of existing and development of new design standards to address the impacts of climate change, including a research plan and cost proposal for immediate submission to Congress (Recommendation 9); and creating a federal-level interagency working group focused on adaptation (Recommendation 11). Most of these initiatives would require federal action; others would require action by professional organizations and university researchers. In all cases, leadership and continuing commitment would be essential.

REFERENCES

Abbreviations

IPCC	Intergovernmental Panel on Climate Change
NRC	National Research Council

IPCC. 2007. Summary for Policymakers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds.), Cambridge University Press, Cambridge, United Kingdom, and New York.

NRC. 2007. *Evaluating Progress of the U.S. Climate Change Science Program: Methods and Preliminary Results.* National Academies Press, Washington, D.C.

APPENDIX A

Detailed Statement of Task

This study will focus on and emphasize the consequences of climate change for U.S. transportation and adaptation strategies. It will summarize possible consequences for transportation, such as from sea-level rise, higher mean temperatures with less extreme low temperatures and more hot extremes, and, possibly, more frequent and severe rain events. U.S. transportation options for adapting to impacts will be analyzed, including possible need to alter assumptions about infrastructure design and operations; ability to incorporate uncertainty in long-range decision making; and capability of institutions to plan and act on mitigation and adaptation strategies at the state and regional levels.

The study will also provide federal, state, and local transportation officials in the United States with an overview of the scientific consensus regarding climate change—including uncertainty about its nature and extent.

Drawing heavily upon analyses already prepared, the study will summarize current and projected contributions of transportation to climate change and the potential effects, costs, and benefits of strategies to reduce transportation's impact. This would include strategies, for example, that affect land use patterns, influence mode choice, and involve alternatively fueled or more efficient motor vehicles.

The study will identify critical areas of needed research. The final report will include findings and recommendations regarding needed research and suggested actions to prepare for the possibility of climate change.

APPENDIX B

Contribution of U.S. Transportation Sector to Greenhouse Gas Emissions and Assessment of Mitigation Strategies

The body of this report describes how climate change is expected to impact the U.S. transportation sector and identifies ways in which this impact might be ameliorated. The committee's charge also directed it to review what is known about the contribution of transportation to greenhouse gas (GHG) emissions:

> Drawing heavily upon analyses already prepared, the study will summarize current and projected contributions of transportation to climate change and the potential effects, costs, and benefits of strategies to reduce transportation's impact. This would include strategies, for example, that affect land use patterns, influence mode choice, and involve alternatively fueled or more efficient motor vehicles.

This appendix addresses this aspect of the committee's charge.

HOW THE TRANSPORTATION SECTOR INFLUENCES CLIMATE CHANGE

Transportation vehicles emit GHGs when fuel undergoes combustion in their engines. The vast majority of these combustion-related emissions consist of carbon dioxide (CO_2).[1] But road transport vehicles also emit

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[1] The U.S. Energy Information Agency's annual publication *Emissions of Greenhouse Gases in the United States* provides estimates of transport sector emissions of CO_2, CH_4, and N_2O. In 2003, CO_2 accounted for 97 percent of the total, when each gas is converted into its global warming

small amounts of nitrous oxide (N_2O) and methane (CH_4). Aircraft operating at high altitudes emit not only nitrogen oxides (NO_x) [which increases the rate of ozone production by speeding the oxidation of carbon monoxide (CO) and CH_4] but also water vapor [which generates contrails that, depending on the time of day they are produced, either reflect solar radiation back into space (daytime) or trap it (nighttime)] (IPCC 1999; see also Stuber et al. 2006).

Transport activity is also associated with two additional categories of emissions: (*a*) those produced in the extraction, production, and distribution of transport fuels and (*b*) those produced in the manufacture, distribution, and disposal of transport vehicles.[2] A rough idea of the relative significance of these additional categories of emissions can be obtained from life-cycle studies that attempt to track all emissions related to a vehicle and its fuel. One of the best known of these studies estimates that the life-cycle CO_2 emissions generated by a 1996-vintage midsize U.S. passenger car using gasoline as its fuel total 263 g/km, of which the vehicle manufacturing cycle (including disposal) accounts for 18 g/km (6.8 percent); the fuel cycle, 49 g/km (18.7 percent); and fuel combustion, 196 g/km (74.5 percent) (Weiss et al. 2000, 5–8).[3]

In this appendix, the committee attempts to provide as comprehensive a picture as possible of transport-related GHG emissions. It was not feasible to include emissions from each life-cycle stage or emissions of each GHG gas; we do, however, take care to identify which emissions are included in the data presented.

CURRENT AND PROJECTED TRANSPORT-RELATED GREENHOUSE GAS EMISSIONS

According to the 2005 edition of the International Energy Agency (IEA) publication *CO_2 Emissions from Fuel Combustion,* worldwide CO_2 emis-

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potential. Nearly all the remainder was accounted for by N_2O (U.S. Energy Information Administration 2004, 31, 49, 62). This publication provides no information on aerosols produced by transport activity, but these are believed to be relatively insignificant.

[2] The second of these categories is of concern only with respect to road vehicles. The number of nonroad vehicles (locomotives, ships, and aircraft) is so small that the GHG emissions related to their manufacture, distribution, and disposal are minimal.

[3] The report assumes 95 percent recycling of metals and 50 percent recycling of plastics. In the report, the emissions figures are stated in grams of carbon per kilometer. For consistency with the other emissions data in this appendix, the figures have been converted here to grams of CO_2 per kilometer.

sions from fuel combustion in 2003 totaled 25.0 billion tonnes (IEA 2005). The transport sector accounted for 5.9 billion tonnes, or 23.6 percent of this total (IEA 2005).[4] Another IEA publication (IEA 2006) provides "reference case" projections of emissions for 2050. According to that report, total CO_2 emissions from fuel consumption in 2050 will be 57.6 billion tonnes (IEA 2006). Transport sector emissions will be 11.7 billion tonnes, or 20.3 percent of this total.

The two IEA publications just cited do not provide a high level of modal detail. However, the World Business Council for Sustainable Development's Sustainable Mobility Project (SMP) has published detailed modal estimates of emissions from fuel combustion for 2000 and projections at 5-year intervals to 2050 (World Business Council for Sustainable Development 2004).[5] The SMP also published estimates and projections of CO_2, N_2O, and CH_4 emissions from the production and distribution of transport fuels. The SMP's figures were generated by a model that was benchmarked to the IEA transport sector totals. Table B-1 shows the estimates and projections generated by this model.

Light-duty passenger vehicles (LDVs), consisting of passenger cars, pickup trucks, sport utility vehicles (SUVs), and minivans, account for the largest share of transport-related emissions. This will continue to be the case even in 2050 if present trends continue. However, emissions from other modes, notably air transport and trucks used to haul freight, are extremely significant and are projected to grow faster than emissions from LDVs.

The SMP report also provides estimates and projections of transport-related emissions by country/region. These are shown in Figure B-1. The United States is included in the region "OECD [Organisation for Economic Co-operation and Development] North America" along with Canada and Mexico.

One notable feature of Figure B-1 is the differences in relative growth rates of emissions within different countries/regions. Generally speaking,

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[4] These are emissions from fuel combustion.

[5] The documentation for this model, as well as the model itself, can be found at www.sustainablemobility.org. The SMP characterizes its projections as what might occur "if present trends continue." For a description of what is meant by the phrase "if present trends continue," see Box 2.1 in the SMP report (p. 27). The report also can be found at the web address just cited. The report draws on 2003 data, the most recent available at the time the report was published. This appendix, which draws heavily on the SMP report, uses 2003 data because it would have been impractical to update the data contained in the SMP report.

TABLE B-1 **World Transport Well-to-Wheels (Vehicle + Upstream) CO_2-Equivalent Emissions by Mode (megatonnes)**

	Year			AAGR (%)	
Mode	2000	2025	2050	2000–2025	2025–2050
Freight + passenger rail	207	341	503	2.0	1.6
Bus	396	436	480	0.4	0.4
Air	733	1,487	2,583	2.9	2.2
Freight truck	1,446	2,423	3,582	2.1	1.6
Light-duty passenger vehicle	2,798	4,152	5,901	1.6	1.4
Two- and three-wheeler	110	209	313	2.6	1.6
Water	638	826	1,015	1.0	0.8
Total	6,328	9,874	14,378	1.8	1.5

Note: AAGR = annual average growth rate.

Source: Data generated by the International Energy Agency/Sustainable Mobility Project (IEA/SMP) Spreadsheet Model.

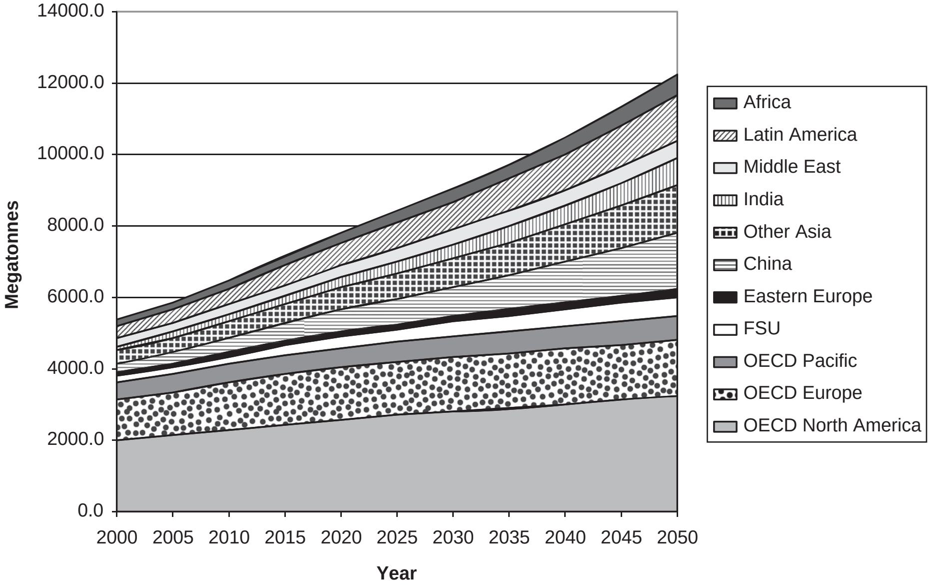

FIGURE B-1 **Transport greenhouse gas emissions by region (all modes).** (*Source:* Data generated by IEA/SMP Spreadsheet Model.)

emissions from countries not presently members of the OECD are projected to grow much more rapidly than emissions from countries that are members of the three OECD regions. The factors responsible for this faster growth are discussed in more detail below.

IEA estimates that U.S. transport-sector emissions from fuel combustion in 2003 totaled 1.8 billion tonnes, of which road transport (LDVs, motorized two- and three-wheelers, buses, medium- and heavy-duty trucks) accounted for 85 percent. The U.S. Environmental Protection Agency (EPA) provides estimates having a greater level of modal detail (see Table B-2). Comparison of the figures from Table B-2 with those from Table B-1 implies that in 2003, U.S. transport emissions of CO_2 from fuel combustion accounted for 30 to 31 percent of total world transport CO_2 emissions from fuel combustion, depending on whether international aviation and marine bunkers are included.[6] The emissions factors developed by the SMP for the production and distribution of each type of transport fuel suggest that including fuel cycle emissions would add another 17.5 percent to the U.S. total (and 15.0 percent to the world total).

EPA does not publish projections of future emissions at a similar level of detail. And, as already noted, the SMP's projections are for OECD North America (i.e., the United States, Canada, and Mexico). According to the SMP data in Figure B-1, OECD North American transport-related emissions will have fallen from 37 percent of the world transport-related total to 26 percent by 2050. This decline in share is accounted for not by any absolute reduction in North American emissions but by the much more rapid rate of growth projected for emissions in regions (other than the other two OECD regions) outside North America.

STRATEGIES FOR REDUCING TRANSPORT-RELATED GREENHOUSE GAS EMISSIONS

The charge to the committee quoted above recognizes that a range of possible approaches exist by which transport-related GHG emissions

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[6] "International aviation and marine bunkers" denotes fuel loaded on transport vehicles in the United States but consumed in international operations. Generally speaking, "international bunkers" are not included in national totals, though they are included in the world totals cited above. The IEA estimates that in 2003, the combustion of international aviation bunkers accounted for 359 million tonnes of CO_2 emissions. The combustion of international marine bunkers is estimated to have accounted for 459 million tonnes of CO_2 emissions.

TABLE B-2 **U.S. CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector, 2003 (Tg CO_2 Eq.)**

	Fuel Type									
Vehicle Type	Gasoline	Distillate Fuel Oil (Diesel)	Jet Fuel	Aviation Gasoline	Residual Fuel Oil	Natural Gas	LPG	Electricity	Mode Total[a]	Mode Share[a] (%)
Road vehicles									1,464.1	78.9
Automobiles	630.2	3.4				0.0			633.6	34.2
Light-duty trucks	460.9	17.6				0.0	0.3		478.8	25.8
Other trucks	39.6	301.1					0.5		341.2	18.4
Buses	0.3	8.0				0.6	0.0		8.9	0.5
Motorcycles	1.6								1.6	0.1
Rail		39.6						3.2	42.8	2.3
Waterborne									82.1	4.4
Ships and boats	17.0				29.5				46.5	2.5
Ships (bunkers)	6.0				18.6				24.6	1.3
Boats (recreational)	11.0								11.0	0.6
Aircraft									230.8	12.4
Commercial aircraft			122.8						122.8	6.6
Military aircraft			20.5						20.5	1.1
General aviation			9.4	2.2					11.6	0.6
Other aircraft			16.3						16.3	0.9
Aircraft (bunkers)			59.6						59.6	3.2
Pipeline						34.8			34.8	1.9
Fuel total[a]	1,166.6	369.7	228.6	2.2	48.1	35.4	0.8	3.2	1,854.6	100.0
Fuel share[a] (%)	62.9	19.9	12.3	0.1	2.6	1.9	0.0	0.2		

Note: Totals may not sum because of independent rounding. LPG = liquefied petroleum gas.

[a] Includes aircraft and waterborne international bunkers.

Source: USEPA 2005, Table 3-7.

might be reduced. The committee believes that the best way of organizing the present discussion of this range of approaches is through the use of the "ASIF decomposition." The CO_2 emissions from fuel combustion by transport vehicles can be characterized by the following equation:

$$G = A * S_i * I_i * F_{i,j}$$

where

G = CO_2 emissions from fuel combustion by transport;
A = total transport activity;
S_i = modal structure of transport activity;
I_i = energy consumption (fuel intensity) of each transport mode; and
$F_{i,j}$ = GHG emissions characteristics of each transport fuel (i = transport mode, j = fuel type).

The product of the first two variables on the right-hand side of this equation, A and S_i, is the demand for transport services provided by transport mode i. The product of the last two variables, I_i and $F_{i,j}$, is the GHG generated by each unit of transportation service provided by mode i using fuel type j.[7]

Historically, the primary driver of transport-related GHG emissions has been the growth of total transport activity (A). The primary offsetting factor has been a reduction in the energy required to produce each unit of transport services (I). However, improvements in transport energy efficiency have been overwhelmed by the increase in transport activity. Changes in the modal structure of transport activity (S) have tended to boost GHG emissions in two ways. First, activity has tended to shift from less energy-intensive transport modes (e.g., rail) to more energy-intensive modes (e.g., truck). Second, in some modes (e.g., LDVs), the load factor (the percentage of vehicle capacity actually utilized) has fallen sharply.[8] Changes in the emissions characteristics of transport fuels (F) have had little impact one way or another.

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[7] This formulation was originally popularized by Lee Schipper. This particular version is taken from IEA (see IEA 2000, 22).

[8] In both trucking and air transport, improvements in average load factors have tended to offset some of the impact of the inherently higher energy intensiveness of the mode. The energy intensiveness of the modes (I) has increased somewhat as a result. (It takes more energy to move heavier average loads.) But the increase in energy required is considerably less than proportional to the increase in load.

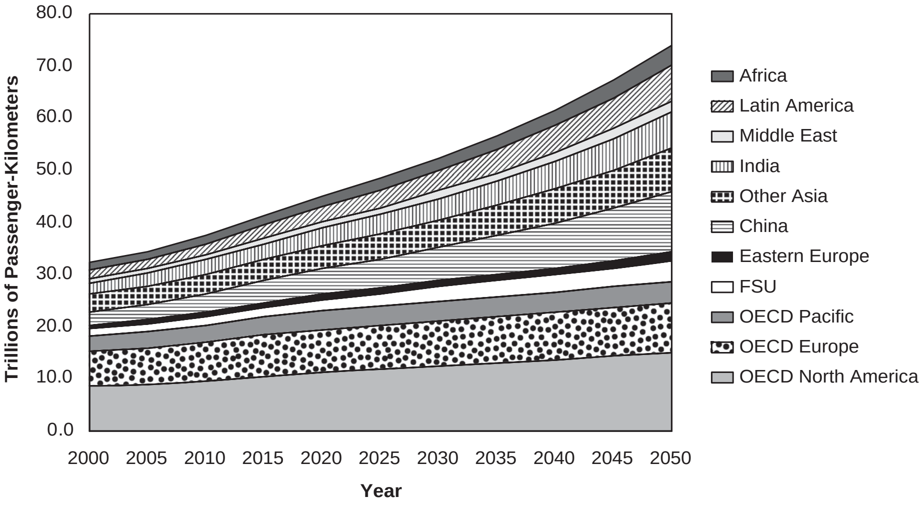

FIGURE B-2 **Passenger transport activity by region.** (*Source:* World Business Council for Sustainable Development 2004, Figure 2-2, p. 30.)

Reducing the Volume of Transport Activity (*A*) or Altering the Modal Structure of Transport Activity (*S*)

The SMP report projects that worldwide personal transport activity, which totaled 32.3 trillion passenger-kilometers (pkm) in 2000, will grow to 74.0 trillion pkm by 2050[9] (see Figure B-2). Worldwide goods transport activity (excluding waterborne),[10] which in 2000 totaled 14.4 trillion tonne-kilometers (tkm),[11] is projected to grow to 45.9 tkm (see Figure B-3). These projections imply average annual rates of growth of 1.7 percent for personal transport activity and 2.3 percent for goods transport activity (again excluding waterborne).

Figures B-2 and B-3 also indicate that rates of growth of both personal and goods transport activity are likely to vary widely across countries/

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[9] Passenger-kilometer is defined as the transportation of one passenger a distance of 1 kilometer.

[10] The SMP report does not project waterborne freight activity. According to the United Nations Conference on Trade and Development (UNCTAD 2005), in 2000, world seaborne trade totaled 23.7 trillion tonne-miles, or 43.9 tonne-kilometers (tkm). Of this total, 41 percent was oil and oil products, 29 percent was the five main dry bulk commodities (including iron ore, coal, and grain), and 30 percent was other dry cargoes (including containerized cargoes). We assume that the "miles" reported by UNCTAD (2005) are nautical miles. If so, this means that in 2000, ocean shipping accounted for 75 percent of all tkm of freight carried.

[11] Tonne-kilometer is defined as the transportation of 1 metric ton (tonne) of freight a distance of 1 kilometer.

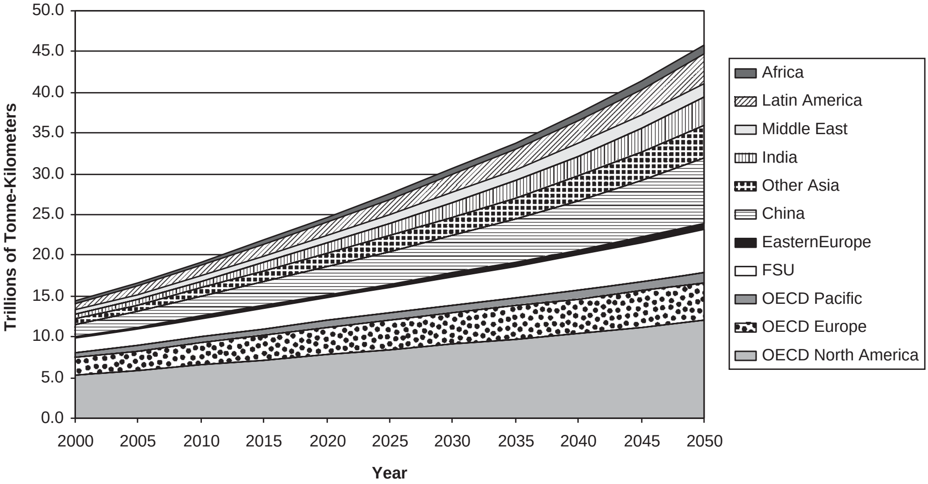

FIGURE B-3 **Goods transport activity (excluding waterborne).** (Note: Waterborne activity not available by country/region. According to the United Nations Conference on Trade and the Environment, in 2000, worldwide waterborne transport activity totaled 43.9 trillion tkm.) (*Source:* World Business Council for Sustainable Development 2004, Figure 2-5, p. 32.)

regions, reflecting basic economic and demographic changes discussed below. At present, the majority of both personal and goods transport activity occurs within or between countries that are members of the OECD.[12] Over the next half-century, however, transport activity is projected to grow much more rapidly in those countries that are not presently OECD members. These higher growth rates, if achieved, imply that non-OECD personal transport activity will exceed OECD personal transport activity by about 2025. The crossover point for goods transport activity is likely to be even sooner—perhaps as early as 2015.

Drivers of the Volume of Personal and Goods Transport Activity

Numerous factors influence the rate of growth of personal and goods transport activity, but the following are especially important: (*a*) the level and rate of growth of real per capita income, (*b*) the rate of population

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[12] The OECD was formed in 1961 by the following countries: Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain Sweden, Switzerland, Turkey, the United Kingdom, and the United States. The following countries have since joined: Japan (1964), Finland (1969), Australia (1971), New Zealand (1973), Mexico (1994), the Czech Republic (1995), Hungary (1996), Poland (1996), the Republic of Korea (1996), and Slovakia (2000).

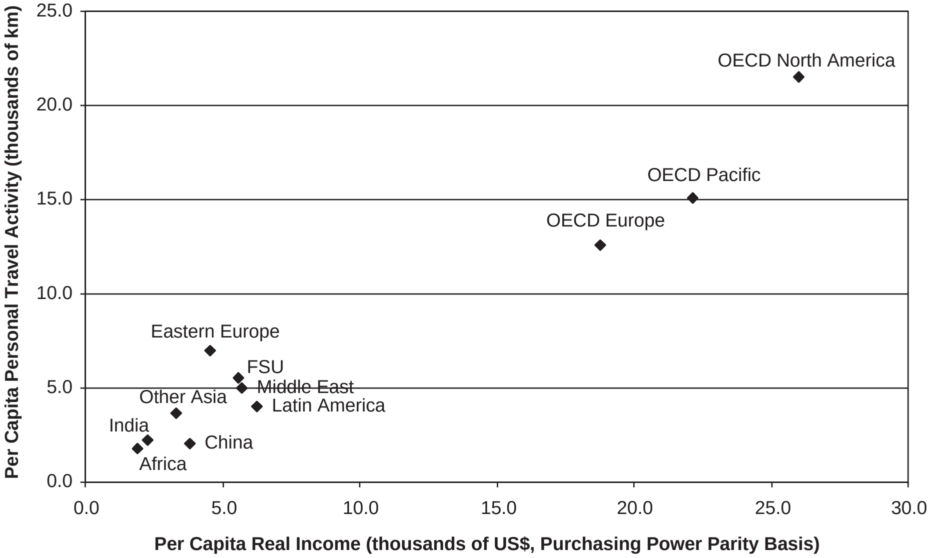

FIGURE B-4 **Per capita personal travel activity versus per capita real income.** (*Source:* Data generated by IEA/SMP Spreadsheet Model.)

growth, (*c*) the share of population residing in urban areas, and (*d*) the spatial organization of urban areas (also called "urban form"). In addition, a potentially salient factor is the impact of telecommuting and the Internet on travel demand.

Level and Rate of Growth of Real per Capita Income Transportation activity both drives and is driven by the level and rate of growth of real per capita income. This should not be surprising. Transportation services are a major enabler of economic growth, and as people become wealthier, they find more reasons to travel. Figure B-4 shows the relationship between real gross domestic product (GDP) per capita and per capita personal travel in 2000 for the countries/regions included in the SMP report.[13] In 2000, the average resident of an OECD country traveled 5.7 times as many kilometers per year as did the average resident of a non-OECD country—a slightly lower ratio than that between the average real per capita incomes of the two country groupings.

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[13] Similar data for goods transport activity are not provided because the information on waterborne origin–destination pairs needed to assign that important transport activity to countries/regions is lacking.

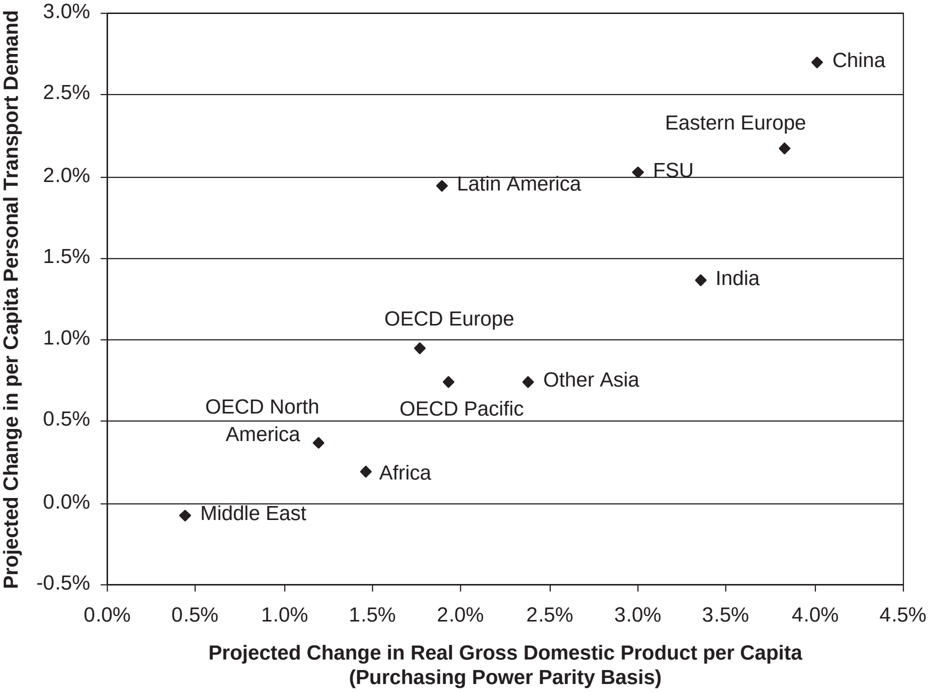

FIGURE B-5 **Projected change in real per capita personal transport demand versus projected change in real gross domestic product per capita (purchasing power parity basis), 2000–2050.** (*Source:* Data generated from IEA/SMP Spreadsheet Model.)

Figure B-5 shows the relationship between the projected rate of change in real GDP per capita and the projected rate of change in per capita personal travel over the period 2000–2050. Note the difference in the relative positions in the two exhibits of the three OECD regions and those non-OECD countries/regions in which economic growth is projected to grow the most rapidly.

Given the relationship between real per capita income growth and per capita personal (and probably also goods) transport activity, it is obvious that if the former were slower, so would be the latter. However, most people (especially those living in countries where real per capita GDP is relatively low today but is projected to grow rapidly) would find highly unpalatable a strategy of deliberately slowing growth in real GDP per capita in order to slow the growth of travel activity. This does not mean that the link between real per capita income growth and per capita travel activity is immutable. But it does mean that if this link is to be weakened, the measures employed will have to be less draconian than limiting economic growth. This issue is revisited below.

Rate of Population Growth The projected trends in real per capita income growth, if realized, will be a powerful force serving to increase transport activity. However, another factor that has exerted a powerful influence in increasing transport activity in the recent past—population growth—will be waning in importance in the future.

Population growth rates are falling everywhere. This should not be surprising. Figure B-6 illustrates how extraordinary population growth during the last half of the 20th century truly was. This explosion of world population was caused by reduced mortality in the less developed regions—a reduction that was not accompanied (at least initially) by declining fertility rates in these regions. One major factor enabling this rapid growth in population was the increased ability to transport food, especially by ship and rail. The growth in population, together with improved transport, stimulated the demand for finished goods. During the last quarter of the

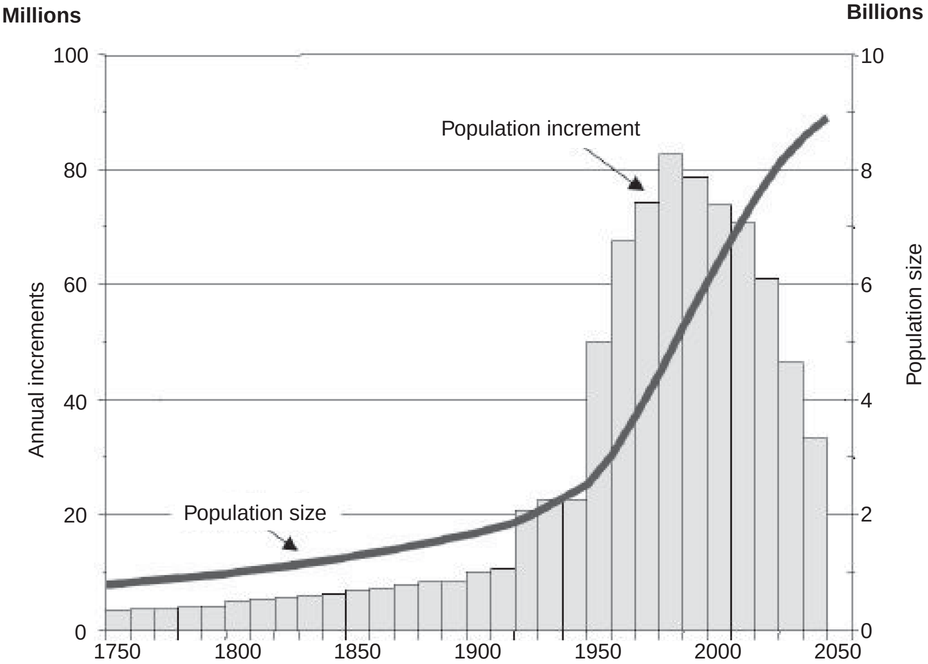

FIGURE B-6 **Long-term world population growth, 1750–2050 (projected).** (*Source:* UN 1999, Figure 1, p. 7. Reprinted with permission of the United Nations Population Division.)

20th century, the rate of population growth began to fall, largely because of declines in fertility.

As with real per capita income growth, the pattern of population growth over the period 2000–2050 will differ by region.

As a result of sharp fertility declines, the average age of the population in many countries will be rising. In 1950, the median age of the world's population was 23.5 years. It is estimated to have increased to 28.1 years by 2005, and by 2050 is projected to reach 37.8 years.[14]

Share of Population Residing in Urban Areas Most personal travel is within or between urban areas. Urban areas depend on transport systems to supply them with food, energy, raw materials, and finished goods. It is not surprising, therefore, to find a link between urbanization and transport activity.

In 1950, about half of the people in the more developed regions lived in cities[15] (see Table B-3). By 2000 this figure had increased to nearly 75 percent.[16] However, the growth in urbanization is tapering off in the countries of the more developed regions. In the next 30 years, the percentage of people living in urban areas in these countries will increase only to 82 percent. The total urban population in these regions will experience a relatively small increase, with most of that increase occurring in North America (the United States and Canada).[17] In contrast, urban populations in countries located in the less developed regions will grow rapidly.

Spatial Organization of Urban Areas (Urban Form) The spatial organization of urban areas exerts an independent influence on the total volume of personal and goods transport activity, as well as on modal choice. When

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[14] The median age of the U.S. population, which was 30.0 years in 1950, is estimated to have reached 36.1 years by 2005 and is projected to grow to 41.1 years by 2050 (UN 2005, Table VIII-12).

[15] The categorization of countries into those located in "more developed regions" and "less developed regions" is used by the United Nations "for statistical convenience and [does] not necessarily express a judgment about the stage reached by a particular country or area in the developing process" (UN 2005, ii). Generally speaking, countries in the more developed regions are members of the OECD, while those in the less developed regions are not. But there are some important exceptions. Russia and the European portions of the former Soviet Union are included in the more developed regions but are not OECD members. Mexico, South Korea, and Turkey are OECD members but are designated by the United Nations as being in the less developed regions.

[16] In 2000, 80 percent of the U.S. population lived in metropolitan areas as defined by the U.S. Census.

[17] The figure for the United States is projected to increase to 87 percent by 2030 (UN 2003, Tables A-3 and A-5).

TABLE B-3 **World Urbanization Trends, 1950–2030 (Projected)**

	More Developed Regions				Less Developed Regions		
	Europe	Northern America[a]	Japan	Regional Total	China	India	Regional Total
Urban Population (billions)							
1950	0.28	0.11	0.03	0.43	0.07	0.06	0.31
1975	0.45	0.18	0.06	0.70	0.16	0.13	0.81
2000	0.53	0.25	0.08	0.88	0.60	0.28	1.97
2030 (projected)	0.55	0.35	0.09	1.01	0.88	0.59	3.93
Change 2000–2030	0.02	0.10	0.01	0.13	0.28	0.31	1.96
Average Annual Rate of Change (%)							
1950–1975	1.9	2.0	3.2	2.0	3.4	3.1	3.9
1975–2000	0.7	1.3	1.1	0.9	5.4	3.1	3.6
2000–2030 (projected)	0.1	1.2	0.2	0.5	1.3	2.5	2.3
Percentage Urban							
1950	51	64	35	53	13	17	18
1975	66	74	57	67	17	21	27
2000	73	79	65	74	36	28	41
2030 (projected)	80	87	73	82	61	41	57
Change 2000–2030	7	8	8	8	25	13	16

[a] Northern America = Bermuda, Canada, Greenland, Saint-Pierre-et-Miquelon, and United States.

Source: UN 2003, Tables A.2, A.3, and A.6. (Reprinted with permission of the United Nations Population Division.)

people talk about eliminating “unnecessary” travel or “unlinking” economic growth from transport activity, they generally are referring to the deliberate alteration of urban areas’ spatial organization to influence the total volume of personal and goods transport activity, the choice of modes by which the demand for that activity is fulfilled, and the capacity utilization rates (i.e., load factors) of the vehicles being used.

How the Spatial Organization of Urban Areas Affects and Is Affected by Transport Activity and Modal Availability Throughout history, the size and shape of cities have been constrained by the ability of their transport systems to supply them with food and raw materials, to enable their residents to congregate in numbers sufficient to convert these raw materials into finished goods efficiently and to conduct other business requiring face-to-face interaction, and to transport their finished goods to distant markets. The development of inexpensive waterborne transportation eased the first and third of these constraints. But cities were still severely limited in size by their ability to move people from their homes to work and back on a daily basis.

Until roughly the middle of the 19th century, the area of a city like London was constrained by the distance people could walk from home to work.[18] The development of railways linking the suburbs and the central business district (CBD), together with the development of means of moving masses of people underground within the CBD, enabled Londoners and residents of other major cities to live much greater distances from their work. However, the availability of these modes of high-speed public transport did not necessarily change the need for people's activities other than commuting to be located within a relatively short distance of where they lived.

Only when automobile availability became widespread did the location constraints on these other activities ease. Indeed, noncommute activities now account for the majority of personal trips and miles traveled in most high-income countries. Table B-4 illustrates this point for the United States with data from the 2001 National Personal Transportation Survey.

The spatial organization of urban activity also affects and is affected by goods transport. Before the advent of the automobile and the truck, nearly all large cities had a single, relatively compact CBD where a large share of the city's employment was concentrated. (In the terminology used by urban planners, these cities were "monocentric.") The location of the CBD was usually determined by its proximity to waterborne (and later to rail) transportation. The development of the motorized truck freed CBDs from these constraints.

Thus, the widespread ownership of motorized road vehicles allowed workers to both live and work almost anywhere they wished within a metropolitan region. The resulting decline in average residential and employment densities has undermined the viability of public transport,

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[18] Indeed, the first traffic count of people entering the 1 square mile City of London between 8 a.m. and 8 p.m. (1854) found that horse-drawn omnibuses were the means by which the largest number of people (44,000) were transported into town; 31,000 arrived by train; and 26,000 entered by using private carriages or hackney cabs. But all these modes of transport were dwarfed by the 200,000 who walked.

TABLE B-4 **Characteristics of U.S. "Daily" or "Short Distance" Personal Travel, 2001**

	Trips	Kilometers
Annual travel (per capita)	1,481	24,459
Purpose of travel		
Commuting/business	18%	26%
School, church	10%	6%
Shopping	19%	13%
Family, personal business, escort	25%	20%
Social/recreational, vacation, visiting friends, and other	28%	35%

Source: CRA International compilation from the 2001 National Household Travel Survey (BTS 2001).

especially rail-based public transport. Only cities that have managed to maintain strong CBDs and that developed high-speed public transport systems before the automobile came to dominate personal travel have managed to keep the share of commuting travel by private car relatively low.[19] And this is only true for workers traveling to work in the CBD; those with jobs outside the CBD generally commute to work by car.

Magnitude of the Impact of the Spatial Organization of Urban Areas on Transport Activity and Modal Choice Studies have demonstrated a statistically significant relationship between the spatial organization of urban areas and the volume of personal travel activity. But just how quantitatively significant is this relationship? Two recent U.S. studies provide information on this question. A Transportation Research Board policy study is also under way that is examining the relationships among development patterns, vehicle miles traveled (VMT), and the energy conservation benefits of denser development patterns.

Ewing et al. (2002) ranked 83 U.S. cities in terms of a "sprawl index" composed of four components: residential density; the neighborhood mix of homes, jobs, and services; the strength of activity centers and downtowns; and the accessibility of street networks. They compiled information on the rate of vehicle ownership, the share of commuters taking transit to work, the share of commuters walking to work, the average commute time,

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[19] The share of commuters working in Manhattan who drive to work is just over 10 percent. The data for commuters working in central London are similar.

TABLE B-5 **How Personal Transportation Demand Is Influenced by Urban Form**

MSA/PMSA Name	Sprawl Index	Vehicles per 100 HH	Transit to Work (%)	Walk to Work (%)	Commute Time (min)	Vehicle Miles Traveled per HH (mi/day)
Average—10 most sprawling	58.86	180	2.1	1.92	26	70.18
Average—10 least sprawling (excluding outliers)	132.29	162	7.0	3.56	26	54.45
Difference—10 most sprawling and 10 least sprawling (excluding outliers)	73.43	–18	4.9	1.64	0	–15.73
Excluding outliers						
Jersey City, N.J. PMSA	162.27	93	34.2	8.71	33	N/A
New York, N.Y. PMSA	177.78	74	48.5	9.61	39	40.19

Note: HH = household; MSA = metropolitan statistical area; PMSA = primary metropolitan statistical area.
Source: Derived from Ewing et al. 2002, Appendix 3.

and the vehicle miles traveled per household per day for each of these cities. Table B-5 shows the average of these transport indicators and the average sprawl index[20] for the 10 "most sprawling" and the 10 "least sprawling" cities. The latter category excludes two clear outliers—New York City and Jersey City[21]—which are shown separately in Table B-5.

The range in the researchers' sprawl index between these two groups of cities—73.43—is almost three standard deviations. Over this range, there is an 11 percent difference in the number of cars per hundred households (180 versus 162) and a 29 percent difference in the number of VMT per household per day (70.18 versus 54.45). For both groups of cities, the share of commuters taking public transit to work averages below 10 percent, and the share of commuters walking to work averages less than 5 percent. The average daily one-way commute time in both groups of cities is identical—26 minutes.

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[20] The sprawl index is scaled so that 25 units is equal to one standard deviation. The index ranges in value from 14.22 to 177.78, with a lower value indicating greater sprawl.

[21] The New York City region (which includes Jersey City) accounts for approximately 40 percent of all U.S. public transport trips.

The second study, conducted by Bento et al. (2005), covered 114 U.S. urban areas. Instead of developing a sprawl index, these researchers used the actual values of different variables that they believe reflect the spatial organization of these urban areas. They used these characteristics, plus other control variables, to predict the average VMT per household, the average probability of driving to work by workers, and the average annual commute miles for the "average U.S. household" if it resided in each urban area. Table B-6 shows these predicted values for six U.S. urban areas: Atlanta, Boston, Chicago, Houston, New York, and San Diego. The difference in predicted average annual VMT per household between Atlanta and Boston (the latter being the "most compact" urban area other than New York City) is 25 percent (16,899 versus 12,704 VMT). The predicted average probability of driving to work by workers does not fall below 70 percent for any city except New York City. The average number of commute miles driven per year ranges between 4,500 and 5,600 miles.

The differences in transport activity and modal choice among U.S. urban areas reported in the above two studies are not trivial, but they need to be placed in perspective. Cities change slowly, and their changes are heavily path dependent. Transforming a city with the spatial organization of Atlanta into one with the spatial organization of Boston would be a tremendous task requiring many decades, if it could be accomplished at all. Making marginal changes over time might be practical, but even this would not be easy. Moreover, marginal changes are likely to yield only marginal results.

Impact of Telecommuting and the Internet on Travel Demand Some have argued that the development of telecommuting and the Internet could reduce travel demand significantly. This does not appear to be happening. Mokhtarian (2003) summarizes the evidence as follows:

> Overall, substitution, complementarity, modification, and neutrality within and across transportation modes are all happening simultaneously. The net outcome of these partially counteracting effects, if current trends continue, is likely to be faster growth in telecommunications than in travel, resulting in an increasing share of interactions falling to telecommunications, but with continued growth in travel in absolute terms. The empirical evidence to date is quite limited in its ability to assess the extent of true causality between telecommunications and travel, and more research is needed in that area. At this point, what we can say with confidence is that the empirical evidence

TABLE B-6 **How Transport Demand Is Influenced by Urban Form**

Characteristic	Minimum[a]	Maximum[a]	Atlanta	Boston	Chicago	Houston	New York	San Diego
Lane density (area of roads per 100 square miles of land)	1.6	10.6	3.9	4.3	4.7	5.2	5.3	4.2
Land area (km^2)	135	7,683	2,944	2,308	4,104	3,049	7,683	1,788
Population	158,553	16,044,012	2,157,806	2,775,370	6,792,087	2,901,851	16,044,012	2,348,417
Density (people/km^2)	446	2,240	733	1,202	1,655	952	2,088	1,314
Rail transit supply (10,000 mi/km^2)	0	5.7	0.7	1.8	1.9	0.0	5.7	0.2
Nonrail transit supply (10,000 mi/km^2)	0.1	4.3	1.0	1.3	2.8	1.4	3.0	1.6
Jobs–housing balance (standardized)	0.12	0.58	0.44	0.28	0.35	0.44	0.41	0.58
Population centrality (standardized)	0.11	0.22	0.11	0.17	0.15	0.13	0.20	0.20
City shape	0.04	0.99	0.26	0.82	0.48	0.80	0.73	0.36
Predicted average vehicle miles traveled per household			16,899	12,704	14,408	15,685	9,453	16,493
Predicted average probability of driving to work by workers			0.87	0.73	0.74	0.90	0.40	0.84
Predicted average commute miles driven			5,450	4,565	4,620	5,641	2,496	5,247

[a] Refers to sample of 114 urban areas.

Source: Bento et al. 2005, p. 477. (Copyright 2005 by the President and Fellows of Harvard College and the Massachusetts Institute of Technology. Reprinted with the permission of the MIT Press Journals.)

> for net complementarity is substantial, although not definitive, and the empirical evidence for net substitution appears to be virtually nonexistent. (p. 43)

However, she issues the following caution:

> The caveat, "if current trends continue," is a nontrivial one. My expectations for the future are largely predicated on the assumption that the real price of travel will continue to decline or at least remain relatively stable. Should the price of travel escalate markedly . . . the substitutability of telecommunications will obviously become more attractive. Shifts towards telecommunications substitution may also occur for reasons such as an increasing societal commitment to more environmentally benign or sustainable communications modes, but experience suggests that such impacts will be modest at best. (p. 54)

Personal and Goods Transport Demand: Summary

Growth in personal and goods transport demand is the most important single factor driving the increase in transport-related GHG emissions. This growth is being propelled by growth in real GDP per capita, by population growth, by urbanization, and by the spatial organization of urban areas (urban form). The latter factor is also causing shifts in modal use (public transport to LDVs for personal transport and rail to truck for goods transport) that likewise serve to boost transport-related GHG emissions.

The correlation between economic growth and increased transport demand has proved to be very robust, but it is not immutable. Reducing it would be a slow process that would require substantial changes in almost every aspect of people's lives. This does not mean that efforts to induce change should not be made; it does mean that such efforts would not likely bear immediate fruit.

Reducing Vehicle Energy Consumption per Unit of Transport Activity (*I*)

Hundreds (if not thousands) of studies describe and analyze the potential of various technologies to reduce the fuel consumption of transport vehicles. Most of these studies focus on personal vehicles—by far the most numerous road vehicles. The majority of the studies also give the greatest attention to improvements in power train technologies. No attempt is made here to provide an encyclopedic account of the results presented in this vast body of material. Rather, the discussion is confined to broad categories of technologies. Addressed in turn are technologies with the potential to reduce the fuel consumption of road vehicles, those with the potential to reduce the fuel consumption of nonroad vehicles, factors influencing the extent to which the potential of a technology to reduce transport-related GHG emissions is realized, and the impact of vehicle capacity utilization (load factor) on energy use.

Technologies with the Potential to Reduce the Fuel Consumption of Road Vehicles[22]

Road vehicles (automobiles, trucks of all sizes, buses, and powered two- and three-wheelers) account for 76 percent of all transport energy use worldwide and for 82 percent of U.S. transport energy use. LDVs (cars, light trucks, and powered two- and three-wheelers) account for the lion's share of this total—46 percent worldwide and 62 percent for the United States. Most of the remainder—24 percent worldwide and 20 percent for the United States—is accounted for by medium and heavy freight trucks.

Engine Technologies Road vehicles utilize one of two fundamental engine technologies—spark ignition or compression ignition. Other technologies, such as gas turbines, have been tried, but have proved unsatisfactory for powering road vehicles. There are, however, a very limited number of vehicles powered solely by electric batteries.

Spark-Ignition Internal Combustion Engines Most spark-ignition engines in use today are fueled by petroleum gasoline, but they also can run on synthetic gasoline derived from gas-to-liquid processes, on ethanol (or blends of gasoline and ethanol), on compressed natural gas, on liquefied petroleum gases, or on hydrogen.

In the intake system of spark-ignition engines, air is mixed with small amounts of fuel. In the past, this process was carried out in the carburetor, where the fuel was drawn into the airflow mechanically. To meet more stringent emissions requirements, the carburetor has been replaced in nearly all engines by port-injection systems or direct-injection systems. The latter are particularly effective in reducing fuel consumption

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[22] The material in this section is an edited version of IEA 2006, Chapter 5.

and CO_2 emissions; this is especially true for several combustion technologies now in development, such as lean-burn technologies.[23]

Conventional engine architectures use valves activated mechanically by one or more camshafts to control the gas flow into the combustion chamber and the expulsion of the exhaust gases. Variable valve control is an advanced system that allows better management of valve timing and substantially reduces the need for the throttle plates in gasoline engines. Some mechanical systems for valve timing have already been introduced. Other systems, based on electromagnetic or electrohydraulic actuation technologies, are currently being developed. Variable valve control can also enable modular use of the engine, completely obviating the need for some of the cylinders when little engine power is required. This solution diminishes fuel consumption even further and has already been introduced in some large cars.

Controlled auto ignition (CAI) is another new combustion process being actively explored to improve fuel economy and lower the exhaust emissions of spark-ignition internal combustion engines. CAI engines use a highly diluted mixture of fuel, air, and residual gases that can autoignite in a four-stroke engine without preheating of the intake air or an increase in the compression ratio.

Technologies that reduce or eliminate pumping losses and throttled operations, combined with turbochargers and technologies that help contain knock, can result in significant reductions in engine size, also allowing substantial fuel economy improvements and reductions in CO_2 emissions. Many in the automotive industry believe engine downsizing—including the use of turbochargers—can reduce engine displacement size by up to 30 percent. Downsizing the engine also has a positive effect on the whole vehicle design, reducing vehicle inertia and therefore engine load.

Almost all recent-model vehicles equipped with a spark-ignition engine are fully capable with low-level ethanol fuel blends, such as E5 or E10 (5 percent and 10 percent ethanol blends, respectively). To use blends of more than 10 percent ethanol, some engine modifications may be necessary because of ethanol's low compatibility with certain materials and elastomer components. Using compatible materials would eliminate

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[23] A lean-burn engine is designed to operate with a very high air-to-fuel ratio under light-load conditions. When little power is required, lower amounts of fuel are injected into the combustion chamber, only in the area around the spark. This reduces the need for throttling and limits NO_x.

these problems, and the use of such materials is already common in some countries, such as the United States and Brazil. The cost of making vehicles fully compatible with E10 is negligible, and the cost remains very low for full compatibility with E85 (an 85 percent ethanol fuel blend.)

If engines were designed exclusively for pure ethanol or ethanol-rich blends, their costs would be roughly the same as today, but their fuel economy (expressed in liters of gasoline equivalent per 100 km) would be better than that of engines designed for conventional gasoline with the same performance.[24] Similar effects would be seen in CO_2 tailpipe emissions. These improvements are possible because the high octane number of ethanol-rich blends, along with the cooling effect from ethanol's high latent heat of vaporization, would allow higher compression ratios in engines designed for ethanol-rich blends, especially those using the most advanced injection systems available, such as direct-injection systems. Technologies such as direct injection and turbochargers that could lead to downsizing of spark-ignition engines also favor the introduction of ethanol as a transportation fuel.

Compression-Ignition Engines Compression-ignition engines (commonly known as diesel engines) are similar to four-stroke spark-ignition engines, with a few essential differences. One difference is that they do not need to be controlled by a throttle. Instead, the power output is controlled by the amount of fuel injected into the cylinder, without airflow limitation. This characteristic reduces the pumping losses that occur in the aspiration phase in spark-ignition engines. Diesel engines do not need spark plugs. The air-fuel mixture used in these engines self-ignites when the fuel is injected into the combustion chamber. As a result, diesel engines can run lean and reach much higher compression ratios than conventional spark-ignition engines.

Diesel indirect-injection engines (the conventional injection technology used in compression-ignition engines until a few years ago) were characterized by fuel delivery in a prechamber designed to ensure proper mixing of the atomized fuel with the compression-heated air. Precise control of fuel delivery was not easy to achieve in these systems. In recent years, indirect-injection systems have been replaced by common-rail sys-

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[24] According to the *Transportation Energy Data Book,* 25th edition (Davis and Diegel 2006, B-3), the combustion of a gallon of ethanol produces only about two-thirds the heat of a gallon of gasoline (75,670 Btu versus 115,600 Btu). This means a gallon of "gasoline equivalent" ethanol consists of about 1.5 gallons of actual ethanol.

tems. These systems still use a pump to store fuel at very high pressure in a reservoir (the common rail), which is connected to the combustion chamber by fuel injectors. Rail systems permit the activation of the injectors rather than the pump, eliminating the buildup of pressure before each individual injection. This makes it possible to control very precisely the amount of fuel injected and the timing of each injection, thereby maximizing performance and optimizing fuel use.

The fact that diesel engines can work with higher compression ratios than gasoline engines and without a throttle favors the use of intake-air compressors, usually in the form of turbochargers. Such compressors are generally coupled with intercoolers and aftercoolers to increase the density of the air entering the combustion chamber. Turbocharged diesel engines, working with common rail and direct injection, are now an established technology. They equip most of the light-duty diesel vehicles sold in Europe and virtually all new heavy-duty trucks sold around the world.[25]

Two important barriers to the increased use of diesel engines have been their relatively high emissions of particulate matter and NO_x. A modern exhaust system for diesel engines includes a two-way oxidation catalyst and, in the most recent versions, a particulate filter.[26] The two-way oxidation catalyst is similar to the catalytic converter used in gasoline-fueled cars. It converts unburned hydrocarbons and CO into CO_2 and water. These converters are not as effective as those used in gasoline-fueled vehicles. On the other hand, CO and hydrocarbon emissions from compression-ignition engines are inherently low because of the leaner fuel mixture. Oxidation catalysts reduce particulate mass by as much as 50 percent. The problem of ultrafine particulates, one of the most dangerous emissions in terms of health effects, remains unresolved at this point.

The aftertreatment of NO_x emissions in diesel engines presents a difficult technical challenge because of the oxygen-rich state of the exhaust under lean conditions. The formation of NO_x can be reduced by using cooled intake-air compression (whereby an intercooler and aftercooler lower the temperature of the air-to-fuel mix in the cylinder) and by exhaust

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[25] Variable valve control, already described for gasoline engines, also offers improvements in diesel engines, although its ability to reduce fuel consumption is lower for compression-ignition engines than for spark-ignition engines because the latter suffer from higher pumping losses.

[26] A diesel particulate filter may take the form of a ceramic honeycomb monolith. It may also consist of sintered metal, foamed metal structures, fiber mats, or other materials. It removes particulate from the diesel exhaust by physical filtration, capturing the particulate matter on its walls.

gas recirculation. Research in the field of aftertreatment systems continues, including efforts to integrate NO_x reduction with particulate filters.

Hybrid Vehicles The term "hybrid" refers to any vehicle that can use different energy sources in combination. Currently, the term usually refers to hybrid-electric vehicles,[27] which are powered by a drivetrain that combines a conventional internal combustion engine (powered by gasoline, diesel, or an alternative fuel) and an electric motor. Hybrid-electric vehicles can be built in a range of engine architectures with varying sizes for the combustion engine and electric motor, each of which involves different trade-offs in terms of cost, efficiency, and performance.

In *series hybrids,* an electric motor drives the wheels and derives its energy from a battery or an engine, generally an internal-combustion engine, used as a power generator.[28] The power generator supplies the average power required to operate the vehicle and accessories, while a battery stores the excess energy and provides it when needed. Like electric vehicles, series hybrids may use regenerative braking to recharge the battery. A further efficiency gain is achieved by the fact that the engine is largely uncoupled from the load because of road conditions and can be kept working at a range of operating points where its efficiency is high. This type of engine use offers advantages for the aftertreatment of exhaust gases.

In *parallel hybrids,* motion is delivered to the wheels by both an internal combustion engine and an electric motor. The internal combustion engine is no longer used exclusively as a power plant, but works jointly with the electric motor to deliver movement to the vehicle. "Mild" parallel hybrids have an electric motor that acts as a starter and can serve as an alternator during braking (regenerative braking), while an internal combustion engine powers the drivetrain. In mild hybrid configurations, the electric motor may also provide extra torque and extra power when needed. The electric motor used in mild hybrids is usually located between the engine and the transmission or, in "light" designs, in the same position as a standard alternator.

Full hybrids can operate in internal-combustion mode, in hybrid mode, or even in all-electric mode, the latter being used mainly for cold starts and for urban driving at ranges below 50 km. The electric energy is stored in large batteries during the periods of internal combustion engine

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[27] There are hybrid vehicles that use hydraulic fluid rather than batteries as a power "accumulator."

[28] Diesel-electric railroad locomotives are series hybrids. Their diesel engine drives a generator that provides power to electric traction motors.

driving and regenerative braking. In some cases, electricity is stored by charging the battery from the grid (plug-in hybrids).

Hybrid drivetrains are a promising technology not only for LDVs but also for heavy- and medium-duty vehicles that operate locally and for urban buses. Hybrid solutions are not particularly suitable for heavy-duty trucks and intercity buses because the driving cycle of those vehicles is characterized by long driving periods at steady speeds.

The main barrier to greater market penetration of hybrid vehicles is their cost, which is still higher than that of competing vehicles, notably diesel. In their most advanced configurations, diesel vehicles offer fuel economies not far behind those of hybrids. Reducing the cost, weight, and size of batteries is the greatest technology challenge facing hybrid development.

Diesel hybrids achieve smaller reductions in fuel consumption relative to hybrids that incorporate gasoline engines; nevertheless, full diesel hybrids may be the most efficient vehicles in the long run. Diesel hybrid engines will be best suited to urban buses and medium freight trucks, although further improvements in battery technology are needed for this type of application.

Table B-7 shows estimates of CO_2 emissions from new midsized U.S. passenger cars equipped with the above engine technologies identified during the three time intervals 2003–2015, 2015–2030, and 2030–2050. On the basis of a 2003–2015 gasoline internal combustion engine vehicle equal to 100, Table B-8 shows an index of the emissions from each engine type during each of the three periods.

Fuel Cell Vehicles A fuel cell is an electrochemical device that converts hydrogen and oxygen into water and produces electricity in the process. Fuel cell vehicles are propelled by electric motors, with electricity produced within the vehicle.

Proton-exchange-membrane (PEM) fuel cells are particularly suited to powering passenger cars and buses because of their fast start-up time, favorable power density, and high power-to-weight ratio. Fueled with pure hydrogen from storage tanks or onboard reformers, PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes with a platinum catalyst. They operate at relatively low temperatures of around 80°C. This has the advantage of allowing the fuel cell to start quickly, but cooling of the cell is required to prevent overheating. The platinum catalyst is costly and extremely sensitive to CO poisoning. Research efforts are

TABLE B-7 **Tailpipe CO_2 Emissions for Midsized U.S. Passenger Cars Using Different Engine Technologies (g/km)**

	Time Period		
Engine Technology	2003–2015	2015–2030	2030–2050
Spark ignition			
Gasoline ICE[a]	130–234	122–219	114–204
Dedicated ethanol ICE[b]	120–215	112–200	103–185
Flexible fuel vehicle ICE[c]	133–239	125–224	116–209
Light hybrid, gasoline ICE[d]	119–214	111–199	103–185
Mild hybrid, gasoline ICE[d]	108–194	99–178	94–168
Full hybrid, gasoline ICE[d]	99–178	94–169	89–160
Compression ignition			
Diesel ICE[e]	108–193	105–188	102–183
Light hybrid, diesel ICE[f]	96–173	94–168	91–163
Mild hybrid, diesel ICE[f]	87–155	83–149	80–143
Full hybrid, diesel ICE[f]	83–148	80–143	77–138

Note: These estimates refer to a midsized vehicle and assume that roughly half of the potential improvements due to advanced vehicle technologies will improve vehicle fuel economy. (In the case of hybrids, this share rises to 100 percent, but hybrid power trains could also be used to increase performance rather than fuel economy.) The estimates also assume that considerable learning and optimization will occur between 2010 and 2050, in addition to large-scale production of the vehicles. Footnotes below indicate assumptions concerning what technologies are introduced and when. ICE = internal combustion engine.

[a] 2003–2015: Conventional engine, stoichiometric combustion, increased use of variable valve control. 2015–2030: Turbocharged engine with direct injection and variable valve control, engine downsizing. Progressive introduction of advanced combustion technologies with NO_x traps. 2030–2050: Downsized turbocharged engine with direct injection and variable valve control using advanced combustion technologies (CAI) with NO_x traps.

[b] 2003–2015: Conventional engine, stoichiometric combustion. 2015–2030: Turbocharged engine combustion with direct injection and variable valve control. Progressive introduction of advanced combustion technologies needing NO_x traps, progressive downsizing. 2030–2050: Turbocharged downsized engine with direct injection and variable valve control, using advanced combustion technologies with NO_x traps.

[c] 2003–2015: Conventional engine, stoichiometric combustion. 2015–2030: Ethanol-hybrid turbocharged engine with direct injection and variable valve control, downsizing. Progressive introduction of advanced combustion technologies needing NO_x traps. 2030–2050: Downsized ethanol-hybrid turbocharged engine with direct injection and variable valve control using advanced combustion technologies with NO_x traps.

[d] 2003–2015: Wide introduction of starter-alternator systems, mild hybrid engines on some models, full hybrids mainly on large LDVs. 2015–2030: Higher penetration of mild hybrids, even on small vehicles, wide diffusion of full hybrids on large LDVs. Large hybrid shares for minibuses and medium freight trucks. ICE improved in light hybrids, slightly less for mild and full hybrids. 2030–2050: A large share of ICE vehicles sold on the market equipped with hybrid systems. ICE improved in light hybrids, slightly less so for mild and full hybrids.

[e] 2003–2015: Second-generation common rail, progressive downsizing. 2015–2030: Turbocharged downsized engine, variable valve control, possibly heat recovery, particulate filter and NO_x trap (or selective catalytic reduction systems, especially on large engines). 2030–2050: Turbocharged downsized engine, variable valve control, and possibly heat recovery. Particulate filter and NO_x trap (or selective catalytic reduction systems, especially on large engines).

[f] 2003–2015: Introduction of starter-alternator systems; hybrid motorizations on large LDVs; initial diffusion of hybrids in buses, minibuses, and freight trucks. 2015–2030: Penetration of mild hybrids on small vehicles, wider diffusion of full hybrids on large vehicles. Larger shares of hybrid buses, minibuses, freight trucks. ICE improved as for diesel engines in light hybrids, slightly less so for mild and full hybrids. 2030–2050: Further cost reductions leading to large shares of new vehicles equipped with hybrid systems. ICE improved as for diesel engines in light hybrids, slightly less so for mild and full hybrids.

Source: IEA 2006, Chapter 5, material taken from Table 5.2, p. 297; Tables 5.3–5.4, pp. 300–301; Table 5.5, p. 309; and Tables 5.6–5-7, pp. 318–319. Reprinted with permission of OECD/IEA.

TABLE B-8 **Index of CO_2 Emissions from a Midsized New U.S. Passenger Car Powered by Engine Type Shown During Period Indicated (g/km; 2003–2015 Gasoline-Powered ICE = 100)**

	Time Period		
Engine Technology	2003–2015	2015–2030	2030–2050
Spark ignition			
Gasoline ICE	100	94	88
Dedicated ethanol ICE	92	86	79
Flexible fuel vehicle ICE	102	96	89
Light hybrid, gasoline ICE	92	85	79
Mild hybrid, gasoline ICE	83	76	72
Full hybrid, gasoline ICE	76	72	68
Compression ignition			
Diesel ICE	83	81	78
Light hybrid, diesel ICE	74	72	70
Mild hybrid, diesel ICE	67	64	62
Full hybrid, diesel ICE	64	62	59

Note: ICE = internal combustion engine.

Source: Derived from Table B-7.

focusing on high-temperature membranes that would allow the use of lower-cost and more robust catalyst systems.

The current cost of PEM fuel cells exceeds $2,000 per kilowatt (kW), but costs could be cut to as low as $100 per kW through mass production and experience with the technology. This reduction in cost might not be sufficient, however. It is believed that the cost of fuel cells must fall to below $50 per kW to make them competitive. Achieving this cost reduction would require fundamental advances in materials technology and the achievement of higher power densities for fuel cells.

Onboard fuel storage is a major challenge. Existing onboard storage options do not yet meet the technical and economic requirements for making them competitive. Safety is also believed to be an issue. Gaseous storage at 350 to 700 bar[29] and liquid storage at –253°C are commercially

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[29] A bar is a unit of pressure. It is equivalent to 14.5 pounds per square inch (psi). Atmospheric pressure is 14.7 psi. So 350 to 700 bar would be approximately equal to 350 to 700 times atmospheric pressure, or 5,000 to 10,000 psi.

available but are very costly. Solid storage (for example, using hydrides) offers potentially decisive advantages but is still under development, with a number of materials being investigated.

At present, in the absence of further breakthroughs, gaseous storage at 700 bar appears to be the technology of choice for passenger cars. However, the cost of the tank is \$600 to \$800 per kilogram (kg) of hydrogen (H_2), and 5 kg of storage capacity is needed to provide adequate range for the vehicle.

Depending on the pace of technological development, the stack cost of a PEM fuel cell could decline to \$35 to 70 per kW by 2030. If this were to happen, the cost of a fuel cell vehicle at that time would exceed that of a conventional internal combustion engine vehicle by \$2,200 to \$7,600.

Determining CO_2 emissions from hydrogen-powered fuel cell vehicles is not straightforward. The fuel cells themselves do not produce any CO_2 emissions. However, as discussed below, the processes used to produce the hydrogen fuel can emit large quantities of CO_2, making the "well-to-wheels" emissions from such vehicles comparable with (and sometimes even higher than) those from conventional gasoline or diesel internal combustion engines.

Nonengine Technologies While reductions in engine energy use attract by far the most attention, other important technologies have the potential to reduce the amount of energy required to propel a vehicle.

Transmission Technologies Engines have ideal ranges of speed at which they can operate. Operating outside these ranges increases fuel consumption and engine wear. A vehicle's transmission allows its engine to operate more closely to its ideal speed while permitting its driving wheels to operate at the speed the driver chooses.

Transmissions use gears to reduce the speed of the engine to the speed of the wheels. The larger the number of gears, the more likely it is that the engine will be able to operate at its ideal speed across a wide range of vehicle speeds and power requirements. But more gears mean more complexity and more internal friction.

Until the 1970s, most LDVs in the United States had three forward gears—low, medium, and high. When fuel prices increased substantially in the late 1970s and early 1980s, vehicles generally added a fourth gear, sometimes called "overdrive." More recently, transmissions have added electronic controls and additional speeds. Today, transmissions with six forward speeds are being introduced, and seven-speed transmissions are not unheard of.

Some vehicles are now equipped with a continuously variable transmission (CVT). CVTs use a system of belts and adjustable-diameter pulleys to permit an infinite number of forward gear ratios. The engine operates at a near-constant speed while the transmission adjusts continually to produce the speed required for the wheels. CVTs have not yet achieved the power-handling capability to be used on the full range of LDV sizes and weights. Also, they have suffered from reliability problems. However, their use has been forecast to increase in the years ahead.

Technologies to Reduce Vehicle Weight The lighter a vehicle, the less fuel it consumes. Vehicle mass can be reduced either by decreasing the size of the vehicle or by changing the materials from which it is made. Lighter cars can be propelled by lighter engines. A light power train, in turn, requires less structural support and allows further reductions in the weight of the vehicle frame, suspension, and brakes.

Steel is currently the main automotive material. Over the past decade, steel made up an average of 55 percent of the weight of a fully fueled car without cargo or passengers. Most of the remaining weight is accounted for by iron (10 percent), aluminum (6 to 10 percent), and plastics. Cost and the eventual need for large investments to modify the vehicle production process are the main barriers to the increased use of lightweight materials. High-strength steel can cost as much as 50 percent more than traditional steels, but less of the material is needed to achieve the same performance.[30] Lighter materials such as aluminum and magnesium cost more than conventional mild steel, but their greater use could lead to improved manufacturing processes, thereby reducing manufacturing costs. Composite materials have extremely attractive properties but cost a great deal more than metals.

Another source of weight reduction is the replacement of mechanical or hydraulic systems by electrical or electronic systems. Steering can be accomplished by electric motors actuated by joysticks rather than by mechanical linkages between the steering wheel and the wheels of the car.

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[30] The type of steel used in vehicles has been changing. In 1977, 60 percent of the weight of the average U.S. domestic car consisted of steel, 90 percent of which was conventional steel—including cold-rolled and precoated steel. By 2003, the total steel share had fallen to 54 percent, with only 75 percent of that total consisting of conventional steel. During both years, the remainder is accounted for by high-strength steel, stainless steel, and other steels.

This is known as "steering by wire." "Braking by wire" also has been developed, as has "shifting by wire" and "throttle by wire."

Lightweight technologies are being introduced progressively and will continue to be developed.

Tire Technologies The energy requirements of the power train can be reduced through the use of energy-efficient tires. For an LDV, fuel consumption can be reduced by 3 to 4 percent through the use of currently available low-rolling-resistance tires. An additional reduction of 1 to 2 percent in fuel consumption can be achieved by accurately monitoring tire pressure. Currently available technologies can automatically sense low pressure and inform the driver.

Technologies to Improve Vehicle Aerodynamics Aerodynamic drag, which is proportional to the square of a vehicle's speed, is the main factor determining a vehicle's need for power at high speeds. At this time, aerodynamic issues affect most seriously long-haulage heavy-duty trucks and intercity buses, and significant improvements are possible for such vehicles. At highway speeds, aerodynamic losses are estimated to account for 21 percent of the energy use of a heavy-duty truck–trailer combination unit.

Technologies to Reduce the Energy Requirements of Onboard Equipment The energy consumption of air conditioners and other onboard appliances can account for up to half of a vehicle's fuel consumption under certain conditions. A number of efforts are under way to reduce the energy used by these devices. A particular focus has been on reducing the energy required to operate a vehicle's air conditioning system. Installation rates for air conditioners, already approaching 100 percent in both North America and the OECD Pacific region, are growing rapidly in Europe. Fewer than 15 percent of LDVs sold in France in 1995 were equipped with air conditioning. By 2000, that rate had risen to 60 percent, and it is expected to reach nearly 100 percent by 2010.

A significant barrier to greater market penetration of energy-efficient onboard components is the fact that the energy consumed by these appliances is not always captured in current vehicle tests.[31] This reduces the incentive for manufacturers to use such devices. The public is largely unaware of the fuel use of onboard appliances and the cost entailed: 1 kW-

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[31] We understand that this is not the case for the United States.

hour (kWh) of electricity generated on board costs just slightly less than 1 liter of gasoline, exceeding by far the cost of electricity generated in central power plants.

Technologies with the Potential to Reduce Fuel Consumption by Nonroad Vehicles While LDVs are, in the aggregate, the largest consumers of transport fuel and emitters of GHGs, vehicles such as medium and heavy trucks, commercial aircraft, locomotives, and large waterborne vessels actually use much more energy per vehicle each year. In 2003, the average U.S. passenger car traveled about 12,000 miles and used about 550 gallons of fuel. The average combination truck (i.e., a tractor unit with one or more trailers) traveled about 62,000 miles and used about 12,000 gallons of fuel. The average commercial aircraft traveled about 900,000 miles and used about 2.3 million gallons of fuel.[32] This appendix has already described technologies applicable to medium and heavy freight trucks and to buses. The discussion now turns to vehicles that do not travel on roads—aircraft, waterborne vessels, and railroad locomotives.

Aircraft Commercial aircraft account for 12 percent of transport energy use worldwide and 8 percent of that in the United States. Since the 1960s, turbine engines fueled by a light petroleum product known as jet fuel have powered virtually all new commercial aircraft. While the combustion process of these turbine engines is quite efficient, the energy required to lift an aircraft and its payload off the ground and propel it long distances at high speeds is formidable. In fact, a large share of the payload transported by any aircraft is its own fuel. Not surprisingly, fuel usage and fuel costs are therefore an extremely important component of the total operating cost of an air transport system, comparable in magnitude with crew costs and ownership and investment costs.

In a review of historical and projected future trends in aircraft energy use, Lee et al. (2001) analyze the relative contribution of different technological improvements and operational factors to reducing the energy intensity of commercial aircraft during the period 1971–1998. As measured by megajoules per revenue passenger kilometer, this energy intensity has declined by more than 60 percent—an average decline of about 3.3 percent a year.

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[32] These data were calculated from data provided in the *Transportation Energy Data Book* (Davis and Diegel 2006) and *National Transportation Statistics 2004* (BTS 2005).

Three technological factors—reduced specific fuel consumption, an increase in aerodynamic efficiency, and improved structural efficiency—have been responsible for much of this decline. Engine efficiency improved by about 40 percent between 1959 and 1995, with most of the improvement being achieved before 1970 with the introduction of high-bypass engines. Other factors include higher peak temperatures within the engine, increased pressure ratios, and improved engine component efficiencies. Aerodynamic efficiency has increased by approximately 15 percent historically, driven by better wing design and improved propulsion–airframe integration. Improvements in structural efficiency have contributed less, despite some improvements in the materials used to construct aircraft. As has also been true for motor vehicles, reductions in aircraft weight produced by these improved materials have largely been traded off for other technological improvements and passenger comfort.

Lee et al. (2001) project that over the next several decades, the energy intensity of commercial aircraft will continue to decline, but at a slower rate—1.2 to 2.2 percent per year, compared with the 3.3 percent average annual decline experienced over the past several decades.

Waterborne Vessels Waterborne transport, including ocean shipping, coastal shipping, and inland waterway transport, accounts for 10 percent of transport energy use worldwide and for 4 percent of U.S. transport energy use. (The U.S. figure includes recreational uses; the world figure does not.)

Almost all commercial vessels are powered by diesel engines. The engines used in large oceangoing ships are the largest ever built. These giant diesels can have up to 14 cylinders, each with a bore of 980 mm and a stroke of 2,660 mm, giving the engine a displacement of nearly 1,000 liters. Most of these very large engines are classified as "slow speed." That is, they operate at about 100 revolutions per minute and are coupled directly to the ship's propeller, eliminating the need for reduction gears.

The diesel engines powering towboats or self-propelled barges on inland waterways are much smaller—about the size of a large diesel-electric locomotive, though there may be more than one such engine. Large towboats on U.S. inland waterways are rated at over 10,500 horsepower. Fuels used by waterborne transport vehicles are "heavy" grades of diesel fuel and an even "heavier" petroleum product known as "residual fuel oil." Typically, these fuels are higher (often much higher) in sulfur relative to other transport fuels.

TABLE B-9 **Marine Emissions, 1996**

Gas Component	Range of Estimated Emissions (Mt)
Carbon monoxide	0.7–1.1
Nonmethane volatile organic compounds	—
Methane	—
Nitrous oxide	—
Carbon dioxide	436–438
Sulfur dioxide, total	5.2–7.8
Generated by combustion of residual fuel oil	5.0–7.0
Generated by combustion of distillate	0.2–0.8
Nitrogen oxides	10.1–11.4

Source: IMO 2000, p. 11. (Reprinted with permission of IMO.)

A report to the International Maritime Organization published in March 2000 details the energy use and emissions characteristics of ocean-going vessels as of 1996 (IMO 2000). Table B-9 shows the emissions estimated to result from the 138 million tonnes of distillate and residual fuel consumed during that year by these ships. The same report identifies and evaluates the impact of a range of technical and operational measures that could be applied to new and existing ships to reduce energy use and CO_2 emissions. Table B-10 summarizes the report's findings concerning technical measures that might be applied.

Railroad Engines[33] Railroad engines account for 3 percent of transport energy use worldwide and for 2 percent of transport energy use in the United States. Most railroad engines use electricity generated externally or diesel fuel carried on board as their primary energy source. For the world as a whole, 27 percent of energy used by railroads is externally generated electricity, 59 percent is diesel, and 12 percent is coal (virtually all in China). Countries vary widely in the extent to which their railroads rely on electric power. Railroads in Canada and the United States are almost totally diesel powered. In Japan, 78 percent of the rail energy used is electrical, and in Europe, 61 percent.[34]

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[33] The International Union of Railways conducted a project, Energy Efficiency Technology for Railways, in which a range of technologies relating to railway energy efficiency including, but not limited to, engine technologies were evaluated. The project can be accessed at www.railway-energy.org/tfee/index.php.

[34] The statistics in this paragraph were calculated from 2003 data provided by IEA.

TABLE B-10 **Marine CO_2 Reductions by Technical Measure**

Measure	Fuel/CO_2 Savings Potential (%)	Subtotal[a] (%)	Total[a] (%)
New ships			5–30
Optimized hull shape	5–20	5–30	
Choice of propeller	5–10		
Efficiency optimized	10–12[b]	14–17[b]	
	2–5[c]	6–10[c]	
Fuel (HFO to MDO)	4–5		
Plant concepts	4–6	8–11	
Fuel (HFO to MDO)	4–5		
Machinery monitoring	0.5–1	0.5–1	
Existing ships			4–20
Optimal hull maintenance	3–5	4–8	
Propeller maintenance	1–3		
Fuel injection	1–2	5–7	
Fuel (HFO to MDO)	4–5		
Efficiency rating	3–5	7–10	
Fuel (HFO to MDO)	4–5		
Efficiency rating + TC upgrade	5–7	9–12	
Fuel (HFO to MDO)	4–5		

Note: HFO = heavy fuel oil; MDO = marine diesel oil; TC = turbocharging.

[a] Potential for reduction from individual measures is documented by different sources; potential for combinations of measures is based on estimates only.
[b] State-of-the-art technique in new medium-speed engines running on HFO.
[c] Slow-speed engines when trade-off with NO_x is acceptable.

Source: IMO 2000, p. 14. (Reprinted with permission of IMO.)

Recent years have seen major improvements in the efficiency of electric locomotives, brought about by the use of AC power. In the case of diesel-powered locomotives, propulsion system developments have focused primarily on improving the power, reliability, and efficiency of the diesel engines used to generate onboard electric energy, as well as the efficiency of the electric traction engines that deliver this energy to the driving wheels. In addition, diesel locomotives have become subject to emissions standards and, in some places, to noise standards.

Interest is growing in the use of fuel cells to provide auxiliary power for diesel locomotives. This would permit the main diesel engine to be shut down when the locomotive is not in use but still has power needs. Idle time constitutes a surprisingly large share of the total time a diesel engine is in operation. A recent study of locomotive duty cycles on Canadian railroads found that engines were idling between 54 and 83 percent of the time. Using either fuel cells as auxiliary power units or the "hybrid" approach described above would permit engines to reduce the amount of idle time substantially. Although fuel use and emissions are much greater when a locomotive is operating at full power than when it is idling, the potential improvements in both are nontrivial.

Factors Influencing the Extent to Which the Potential of a Technology to Reduce Transport-Related Greenhouse Gas Emissions Is Realized

One of the most controversial issues in the debate over the use of new technologies to reduce GHG emissions is how effective these technologies will be when incorporated into actual transport vehicles in normal service. Invariably, ex post analyses of actual emissions reductions fall short (sometimes considerably short) of their original claimed potential. The discussion below reviews some of the more important factors that tend to create this result.

Extent to Which a Technology's Potential to Reduce Energy Consumption Is Incorporated into the Vehicles in Which It Is Employed Most vehicle technologies with the potential to reduce fuel consumption offer vehicle designers a range of possibilities for how they may be used. Depending on the decisions made by the designer, the share of this potential that is actually used to reduce fuel consumption can vary from zero to 100 percent.

The history of LDV fuel economy in the United States since the mid-1980s provides a textbook example. The bottom line in Figure B-7 shows the corporate average fuel economy (CAFE) of the new light vehicle fleet as tested by EPA. New LDV CAFE rose sharply between 1979 and 1982, increased slowly from 1983 through 1987, declined slowly from 1987 through 1994, and has remained nearly constant since.

This does not mean that vehicle technologies related to fuel consumption have failed to improve since the mid-1980s. EPA uses a measure known as ton-miles per gallon as an (imperfect) reflection of changes in the energy efficiency potential of the technologies actually incorporated into vehicles. The top line of Figure B-7 tracks this indicator. It has grown relatively steadily at a rate of about 1 to 2 percent per year throughout the

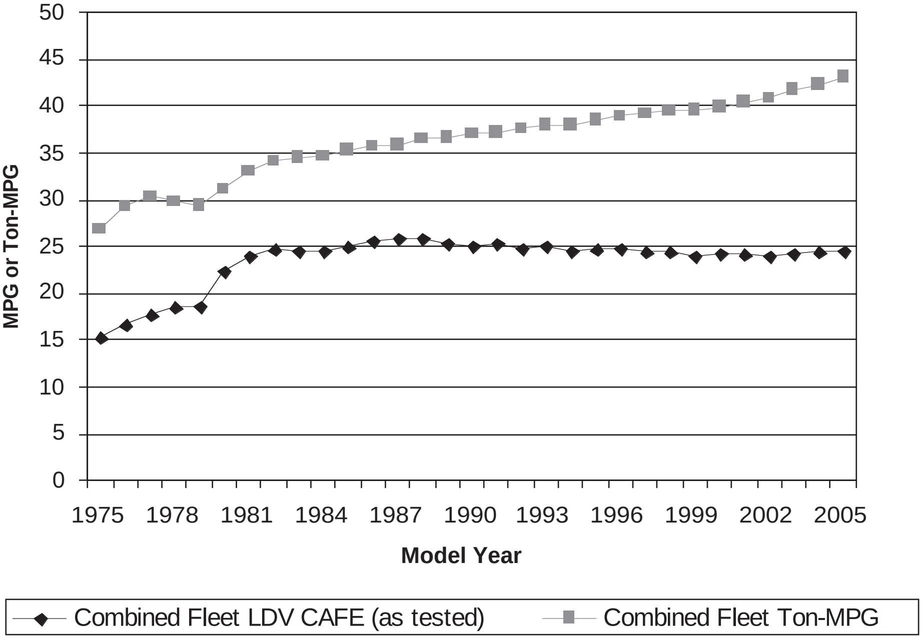

FIGURE B-7 **U.S. light-duty vehicle corporate average fuel economy and technology capability.** (Note: MPG = miles per gallon.) (*Source:* Heavenrich 2005, Table 1, p. 10.)

period, reflecting the new technologies that have been introduced and disseminated throughout the new vehicle fleet.

What explains the sharp contrast between the two lines in Figure B-7? The brief answer is that for much of the period, most of the fuel economy improvement potential has been used by vehicle designers to improve vehicle performance, not fuel economy. Figures B-8*a* and B-8*b* show, respectively, the evolution of passenger car and light truck acceleration performance (measured as 0–60 mph time) between 1975 and 2006. Figures B-9*a* and B-9*b* show similar data for the evolution of vehicle inertia weight.[35] The sharp decline in inertia weight, rather than any radical change in vehicle technology, largely explains the dramatic improvement in new vehicle fleet fuel economy that occurred between the late 1970s and the early 1980s. By the mid-1980s, as new energy-saving technologies began to be introduced in a major way into LDVs, average vehicle weight

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[35] Inertia weight is defined as the curb weight of the vehicle (including fuel) plus 300 pounds.

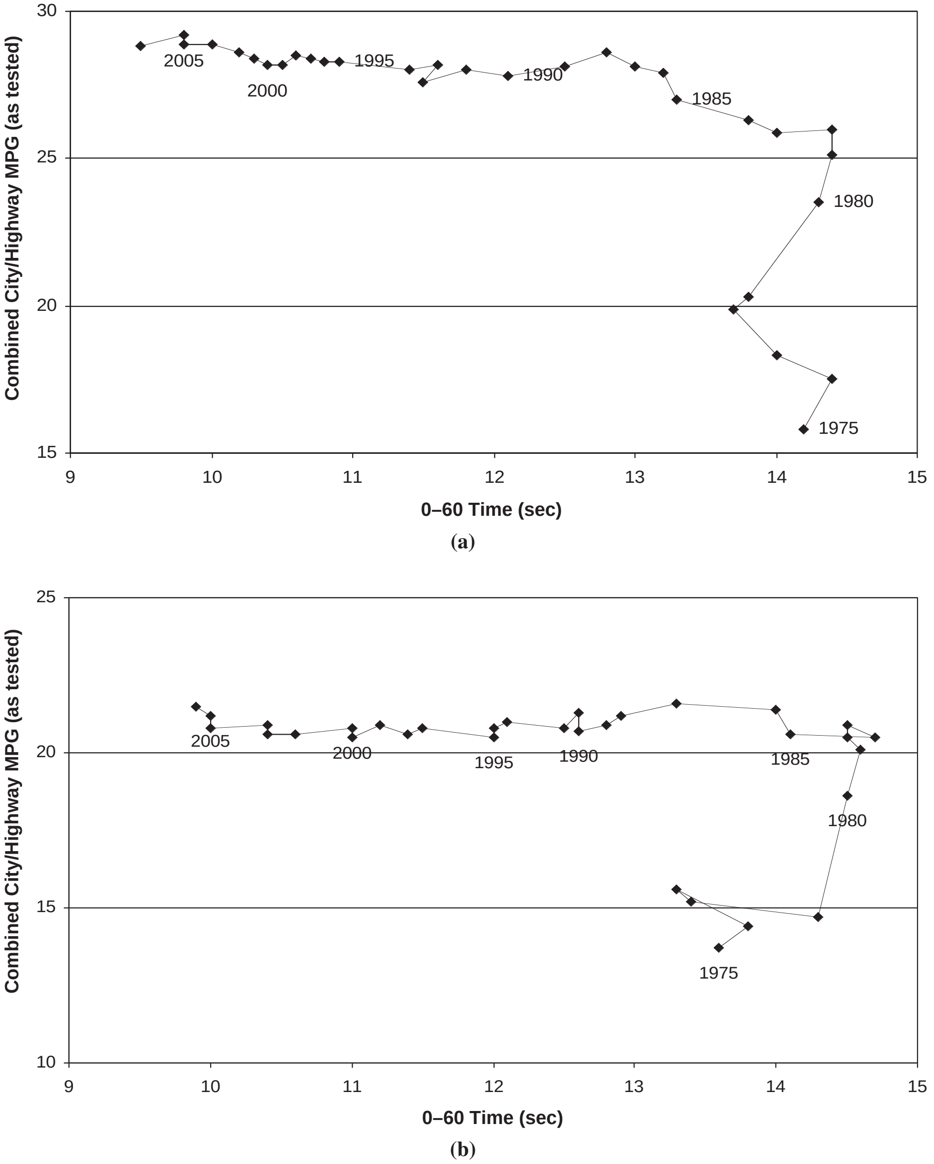
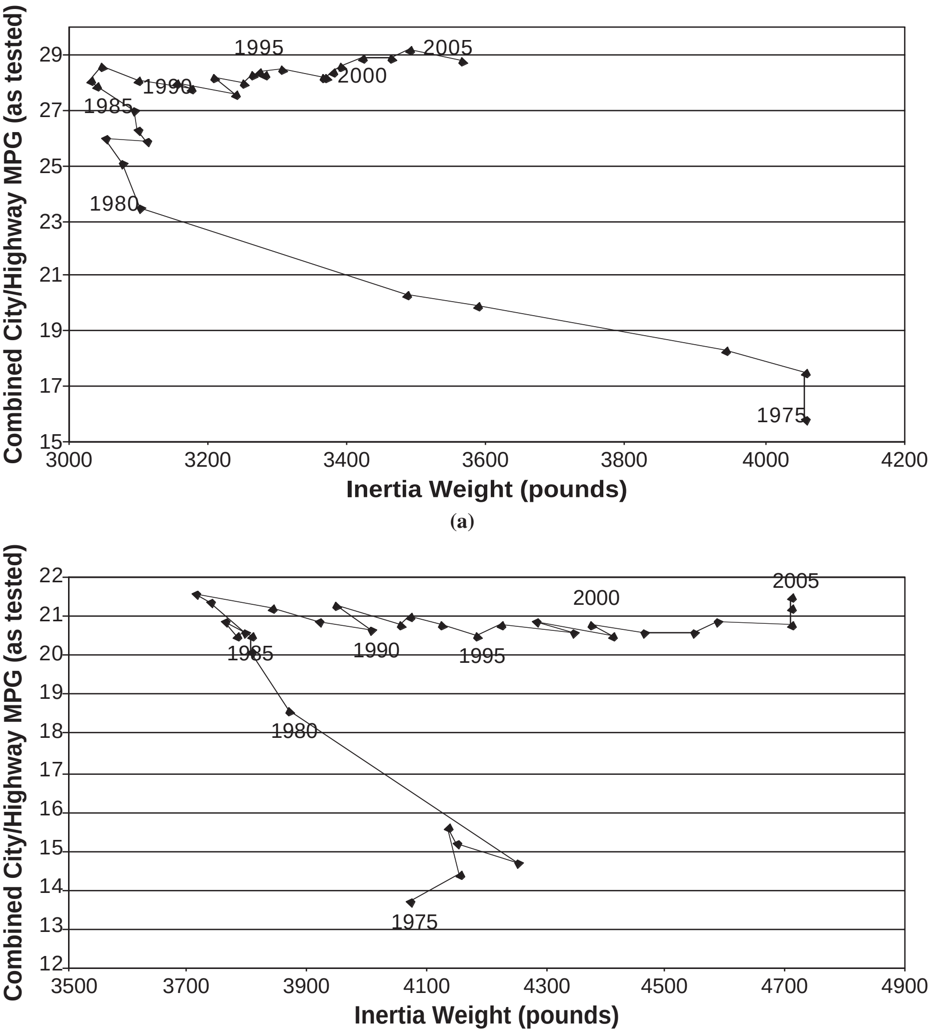


FIGURE B-8 **(*a*) Car and (*b*) truck 55/45 laboratory MPG versus 0–60 time by model year.** (*Source:* Heavenrich 2006, Figures 6 and 7, p. 16.)



(a)

(b)

FIGURE B-9 **(*a*) Car and (*b*) truck 55/45 laboratory MPG versus inertia weight by model year.** (*Source:* Heavenrich 2006, Figures 8 and 9, p. 17.)

began to increase, and acceleration performance, which had remained relatively constant (or even deteriorated somewhat) between 1975 and 1980, began to improve.

The increase in average weight resulted from two interrelated factors. First, the average inertia weight within each vehicle size class grew. Second, larger size classes made up a greater share of the total vehicle market. In particular, a greater share of the new LDV fleet began to be accounted for by light trucks, especially vans and SUVs (see Figure B-10). By 2006, the weight of the average LDV had exceeded its 1975 level. The acceleration performance of both fleets of vehicles had improved dramatically.

The 2005 edition of the EPA report just referenced (Heavenrich 2005) estimates the impact of vehicle weight and vehicle performance on the "laboratory" (or "as tested") fuel consumption of new U.S. passenger cars, light trucks, and all LDVs. Table B-11, adapted from this report, shows these results. The top line of the table shows the actual "laboratory" (or "as tested") "combined" fuel economy (mpg) for new model year 2005 cars, trucks, and the total LDV fleet. The next two rows show estimates of what the 2004 fuel economy would have been had the inertia weight and 0–60 acceleration time been what they were in 1981 and 1987. The final two rows show similar results for size (interior volume) and 0–60 acceleration time. In all cases, the model year 2004 fleet would have exhibited improved fuel economy performance, with the increase in some cases being as high as 30 percent.

Automobile manufacturers assert that these developments merely reflected changes in consumer tastes as fuel prices fell sharply in the mid-1980s and remained low in inflation-adjusted terms thereafter (until recently). Environmentalists assert that the path of fuel economy improve-

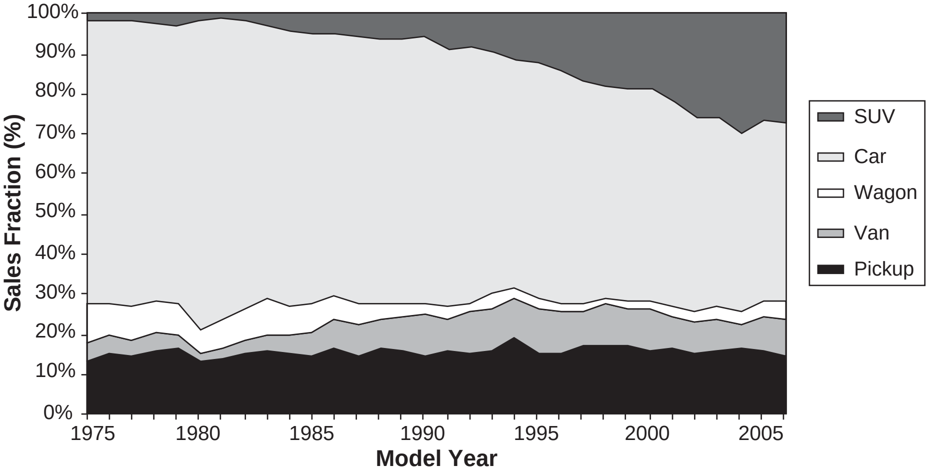


FIGURE B-10 **Sales fraction by vehicle type (3-year moving average).** (*Source:* Heavenrich 2006, Figure 10, p. 18.)

TABLE B-11 **Effect of Performance, Size, and Weight Distribution on Laboratory 55/45 Fuel Economy**

	Laboratory 55/45 Fuel Economy (MPG)			Percent Change from 2005 Actual Averages		
Scenario	Cars	Trucks	Both	Cars	Trucks	Both
2005 actual average	28.8	21.3	24.5			
Model year 2005 averages recalculated using 1981:						
Weight distribution	31.9	30.2	31.0	10.8	41.8	26.6
Size distribution	28.4	21.2	24.3	–1.4	–0.5	–0.9
0–60 distribution	29.8	20.9	24.6	3.5	–1.9	0.3
Weight and 0–60	36.4	28.5	32.0	26.4	33.8	30.5
Size and 0–60	37.1	25.0	29.9	28.8	17.4	22.0
Ref. 1981 actual average	25.1	20.1	24.6	–12.8	–5.6	0.4

Source: Adapted from Heavenrich 2005, Table 24, p. 72.

ments over time reflects the failure of the U.S. government to increase its vehicle energy efficiency standards once they reached their peak in the mid-1980s. Whatever the reason, technological improvements have not automatically translated into improved fuel economy over much of the period shown.

Length of Time Required Between the First Commercial Use of a Technology and When Its Impact on Fuel Consumption Is Felt Throughout the Entire Vehicle Fleet New technologies are not introduced across a manufacturer's entire fleet at one time. EPA has collected data showing the length of time required to achieve various rates of fleet penetration for successful new LDV technologies in the United States (Heavenrich 2006, 62). Fifty percent penetration rates of 10 years are not unusual, and 75 percent penetration rates can easily take 20 years to achieve.

Transport vehicles tend to last a long time. Half the cars built during the 1990 model year were still on the road when the 2007 model year vehicles were first introduced. Heavy trucks last even longer. On the basis of "minimal preliminary data," the expected median lifetime for a model year 1990 heavy truck is 29 years (Davis and Diegel 2006, Tables 3-8 and 3-10).

Commercial aircraft are also very long-lived. DC-3 aircraft built 50 years or more ago are still in commercial service in parts of the world. Boeing estimates that 8,800 of the world's fleet of 17,000 commercial aircraft that were operating in 2005 will still be operating in 2025 (Boeing Company 2006, 6).

Table B-12 shows estimates made by MIT's Laboratory for Energy and the Environment as to how long it might take for various new LDV technologies to have a significant impact on energy use and GHG emissions.

How Motorists Actually Operate Their Vehicles The way vehicles are operated has a significant influence on fuel consumption. Governments test the fuel consumption performance of LDVs on dynamometers that are programmed to follow a set sequence of actions (accelerating, stopping, operating at high speed, operating at low speed, etc.) for specific intervals of time. Their ratings of vehicles' fuel consumption are based on these tests. However, vehicle operators typically do not operate their vehicles as implied by these test procedures. They accelerate more rapidly, drive faster, and so on. This produces a significant gap between "as tested" and "in-use" fuel consumption. For reporting purposes (but not for regulatory compliance purposes), EPA currently adjusts "as tested" mpg downward by 15 percent to make it more comparable with the fuel economy vehicle users are likely to experience in practice. However, the agency believes that this adjustment factor, which is about two decades old, is outdated and proposes increasing it to approximately 22 percent. According to EPA, adoption of this new adjustment factor would result in the 2006

TABLE B-12 **Timescales for New Light-Duty Vehicle Power Train Technologies**

	Implementation Phase (years)			
Vehicle Technology	Market Competitive	Penetration Across New Vehicle Production[a]	Major Fleet Penetration[b]	Total Time for Impact
Turbocharged gasoline engine	5	10	10	20
Low-emissions diesel	5	15	10–15	30
Gasoline hybrid	5	20	10–15	35
Hydrogen fuel cell hybrid	15	25	20	55

[a] Accounts for more than one-third of new vehicle production.
[b] Accounts for more than one-third of all mileage driven.

Source: Heywood 2006, p. 62. Copyright 2006 by Scientific American, Inc. Reprinted with permission. All rights reserved.

U.S. new vehicle fleet's adjusted fuel economy being reduced from its "as tested" level of 24.6 mpg (9.6 L/100 km) to 19.1 mpg (12.3 L/100 km). Using the current 15 percent adjustment factor, the adjusted fuel economy for the 2006 U.S. new vehicle fleet is 21.0 mpg (11.2 L/100 km) (Heavenrich 2006, A.10–A.14).

Impact of Vehicle Capacity Utilization (i.e., Load Factor) on Energy Use
In the analysis thus far, reductions in energy use per vehicle kilometer have been treated as producing corresponding reductions in energy use per passenger kilometer or tonne-kilometer. The latter two measures, not the former, represent the fulfillment of transport demand. Increasing a vehicle's average load of passengers or freight, while increasing energy use somewhat, normally leads to a reduction in the energy required to produce a given volume of transport services. Fitting vehicle size to demand is an important consideration in minimizing transport energy use.

Different transport modes have experienced varying degrees of success in improving the capacity utilization of their vehicles. In the case of U.S. commercial aviation, the increase in average load factor from about 55 percent in 1975 to the 80+ percent levels being experienced today is responsible for a major share of the industry's energy efficiency improvement per passenger kilometer. The average load factor of freight trucks has also increased. However, U.S. LDV load factors have shown the opposite trend. Between 1977 and 2001, the average number of occupants per vehicle declined from 1.9 to 1.6 passengers, or by 14 percent (Hu and Reuscher 2004, Table 16, p. 31). This helps explain why the number of Btu's required to propel the average U.S. passenger car 1 mile fell from 9,250 in 1970 to 5,572 in 2003 (i.e., by 40 percent), while the number of Btu's required to move one passenger 1 mile fell only from 4,868 to 3,549 (i.e., by 27 percent) over the same period (Davis and Diegel 2006, Table 2-11, p. 2–13).

The percentage of a vehicle's available capacity that can be used is the result of a complex trade-off between cost and convenience. No form of commercial transport can operate at 100 percent of capacity all the time. But as operating costs increase, people are willing to sacrifice convenience to reduce cost, and load factors rise. Public transport systems are especially sensitive to this trade-off. As noted above, low residential densities and the decline of CBDs as the location of most jobs have reduced the number of people wishing to travel from one given point to another, especially during peak hours. Maintaining a level of service frequency and service coverage necessary to make public transport services attractive has collided with the need to use larger vehicles to reduce per seat labor, energy, and capital costs.

Vehicle Fuel Consumption: Summary
New technologies have the potential to reduce substantially the energy used by transport vehicles. The time required to develop, commercialize, and disseminate new vehicle technologies probably is shorter than the time required to alter the fundamental drivers of personal and goods transport demand, but it is still measured in decades. In addition, there is the problem of ensuring that the potential of new technologies to reduce energy consumption in transport is actually realized. As the example of U.S. LDVs after the mid-1980s shows, there is no guarantee that this will occur. Fuel consumption is but one of many attributes of vehicle performance. Unless conditions are right (or can be made right), it is possible that some (or even all) of this potential will end up improving these other performance attributes rather than reducing vehicle fuel consumption.

Altering the Greenhouse Gas Emissions Characteristics of Transport Fuel (*F*)

Gaseous and liquid transport fuels can be produced from a wide range of primary energy sources (see Figure B-11). Depending on the feedstock used and the production method employed, CO_2 emissions (sometimes referred to as "well-to-tank" or WTT emissions) can vary widely, sometimes even being negative. As noted above, changes in the GHG emissions characteristics of transport fuels have not contributed much one way or the other to changes in transport-related GHG emissions over the past several decades. This is due to the present overwhelming dominance of petroleum-based fuels in transport and to the fact that all petroleum-based transport fuels emit approximately the same amount of CO_2 per unit of energy they provide (see Table B-13). In the future, however, WTT emissions are likely to have much greater significance in determining total transport-related GHG emissions.

Figure B-12, from the SMP's final report, shows estimates of the "well-to-tank," "tank-to-wheels" (TTW, sometimes also called "tailpipe emissions"), and "well-to-wheels" (WTW) emissions (the sum of WTT and TTW emissions) generated by a wide range of vehicle–fuel combinations. The figure illustrates that for transport fuels such as hydrogen and for power train technologies such as fuel cells, the WTT portion totally dominates total transport-related CO_2 emissions.

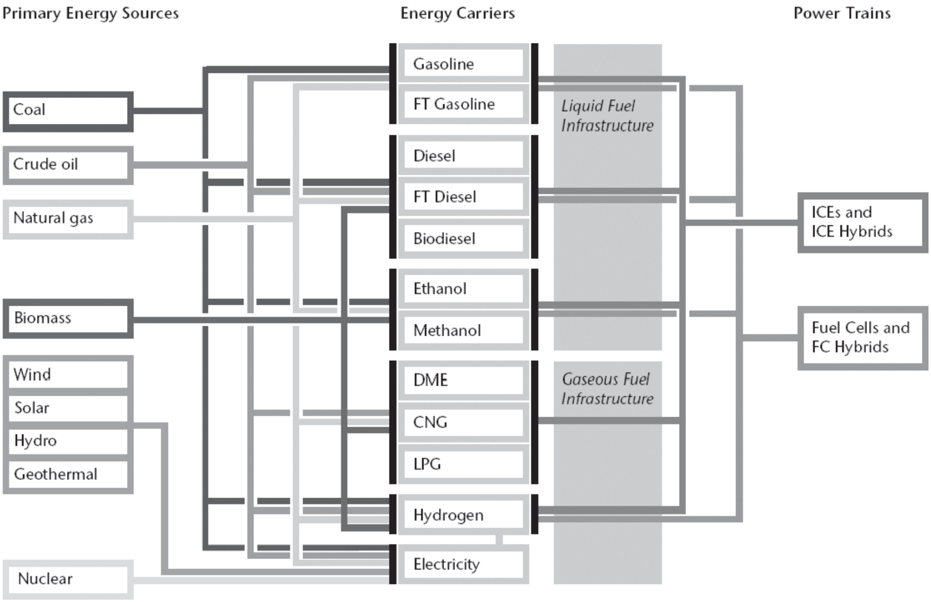
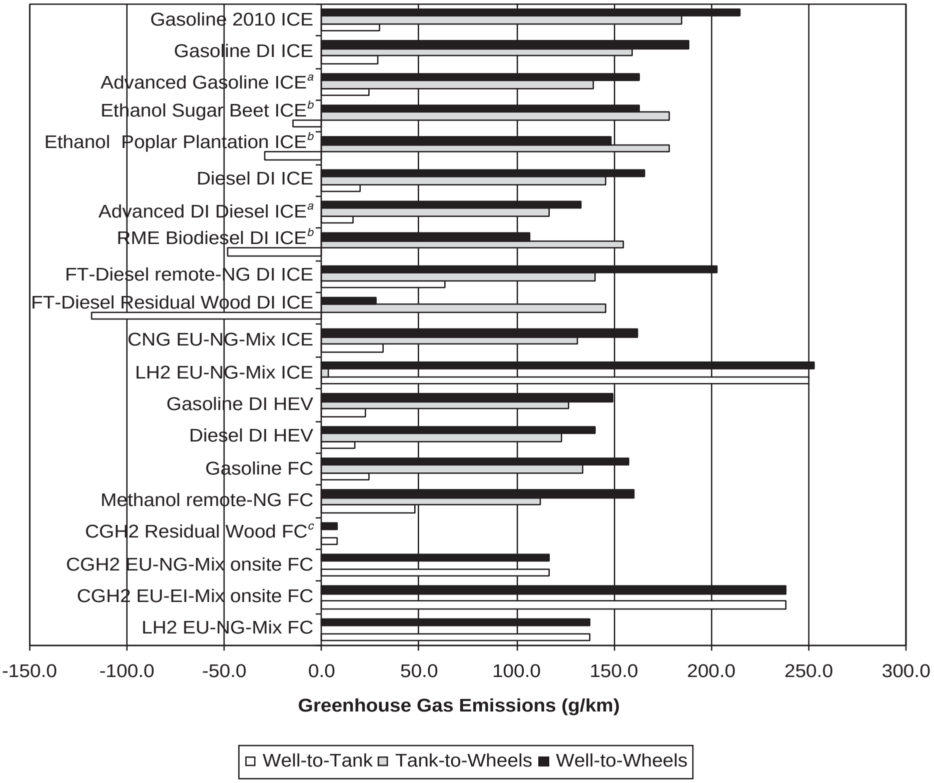


FIGURE B-11 **Possible transport fuel pathways** (CNG = compressed natural gas; DME = dimethyl ether; FC = fuel cell; FT = Fischer–Tropsch; ICE = internal combustion engine; LPG = liquefied petroleum gas). (*Source:* World Business Council for Sustainable Development 2004, Figure 3.1, p. 67.)

TABLE B-13 **CO_2 Emissions per Liter (Gasoline Equivalent)**

Fuel	CO_2 Emissions (kg/liter)	Index (Gasoline = 100)
Gasoline	2.416	100
Diesel (distillate)	2.582	107
Jet fuel	2.491	103
Ethanol	2.484	103
Biodiesel	2.672	111
Residual fuel (bunker fuel)	2.697	112

Source: Data generated from IEA/SMP Spreadsheet Model.



[a] Estimated by the Institute for Internal Combustion Engines.
[b] Estimated by British Petroleum, from General Motors data.
[c] Net output from energy use in conversion process.

FIGURE B-12 **Well-to-wheels (well-to-tank + tank-to-wheels) GHG emissions for various fuel and propulsion system combinations** (CGH_2 = gaseous hydrogen; CNG = compressed natural gas; CO_2 = carbon dioxide; DI = direct injection; EU = European Union; FC = fuel cell; FT = Fischer–Tropsch; HEV = hybrid electric vehicle; ICE = internal combustion engine; LH_2 = liquid hydrogen; NG = natural gas; RME = rapeseed methyl ester). (*Source:* World Business Council for Sustainable Development 2004, adapted from Figure 3.3, p. 77.)

The wide range in WTT emissions for the various fuels illustrated in Figure B-12 results largely from three factors:

- The growing of biomass used to manufacture biofuels (and possibly hydrogen) removes CO_2 from the atmosphere. Gathering and processing the biomass into fuel takes energy and results in the emission of CO_2. This offsets some of the CO_2 removed from the atmosphere by the growing of the biomass. But under plausible assumptions, net WTT CO_2 emissions for biomass-derived fuels can still be negative.

- The production process for some biofuels (e.g., ethanol from corn) generates coproducts that can displace other products that require energy to produce and whose production emits CO_2. How these "coproduct credits" are allocated has a major impact on a biofuel's costs, the energy required to produce it, and its WTT CO_2 emissions (Farrell et al. 2006).
- The production of transport fuels from nonpetroleum fossil carbon sources (e.g., coal or natural gas) generates substantial CO_2 emissions. However, if these emissions can be sequestered, the WTT emissions from the production of these fuels can be reduced to nearly zero.

Analysts differ on how each these factors should be treated in "scoring" the WTT emissions characteristics of different transport fuels produced by different processes from different primary energy sources. Therefore, anyone reviewing the literature on this topic can expect to encounter a range of estimates. The important thing now universally acknowledged is that WTT emissions must be incorporated into any estimates of future transport-related CO_2 emissions.

Fueling Infrastructure

A vast supply infrastructure has developed to deliver petroleum-based transport fuels to the vehicles that utilize them. As noted earlier, motor vehicles can use some alternative fuel blends (e.g., E5 and E10) without major modifications either to their engines or to their fuel systems. The same is true of the current fuel supply infrastructure. Today's petroleum product pipelines routinely carry gasoline, diesel fuel, jet fuel, and propane. They also can carry "mild" blends of gasoline and biofuels (such as E5 and E10). But they cannot carry blends consisting of a majority of biofuels (such as E85) or 100 percent ethanol. The only gaseous transport fuel carried by pipeline is natural gas. Other gaseous transport fuels (in particular, hydrogen) would require dedicated pipelines.

Another very important part of the transport fuel infrastructure is the fueling stations that actually deliver fuel to vehicles. Most of these are not directly connected to a pipeline. Instead, they are supplied by tank trucks that haul fuel from a distributing point (that is connected to a pipeline) to individual fueling stations.

One of the most formidable challenges facing any new transport fuel would be the establishment of an infrastructure capable of distributing it widely. The enormous fixed costs involved in establishing such an infrastructure mean it would not be established without assurance that the demand for the products it would transport would be forthcoming. Yet the vehicles that would be the source of this demand would not be built and purchased without assurance that fuel to power them would be available.

Efforts are being made in some states to establish "hydrogen highways." These are routes along which enough hydrogen refueling stations have been established to permit drivers of hydrogen-fueled vehicles to travel on them. These stations are supplied by tanker trucks. While this could help build initial demand for hydrogen as a transport fuel, it is not a long-term solution to the fuel infrastructure problem.

HOW MUCH AND OVER WHAT TIME PERIOD MIGHT TRANSPORT-RELATED GHG EMISSIONS BE REDUCED?

This appendix has described a wide range of technological and non-technological means of reducing transport-related GHG emissions. In this final section, the committee attempts to indicate how much transport-related GHG emissions might be reduced given the trends thus far described.

As stated at the outset, the fundamental challenge is to reduce the emissions produced per unit of transportation services provided more rapidly than the demand for transportation services grows. While it may be possible to reduce the rate of transportation demand growth somewhat without harming economic growth unacceptably, the committee is aware of no forecast that projects that transportation demand will fail to grow relatively rapidly in the decades ahead, especially in many of the world's less developed countries. The bulk of the responsibility for reducing emissions will therefore fall on improved vehicle technologies and low-carbon or carbon-free fuels.

There is considerable uncertainty about what it might cost to commercialize and widely disseminate many of the more advanced vehicle technology and fuel solutions. Given what is known about projected demand growth, however, it is possible to simulate what might be feasible trajectories of advances in vehicle technology and fuel substitution.

To obtain a better sense of the potential impact of various technologies and fuels in reducing transport-related GHG emissions, the SMP conducted a number of simulations using its spreadsheet model. The benchmark was the SMP reference case projection showing total transport-related CO_2 emissions doubling between 2000 and 2050, with most of the growth in emissions occurring in the countries of the developing world. While other analyses have examined this issue for individual developed countries or regions, to the committee's knowledge, the SMP was the first to examine it for the world as a whole.

In these simulations, the focus was on total road transport. The exercise did not examine the technical or economic feasibility of any of the actions being simulated. It was intended merely to help the SMP understand the impact on GHG emissions from road vehicles if the actions described were taken. This enabled the SMP to compare its results with those of other studies that likewise did not consider technical or economic feasibility in deriving their results.

Single-Technology Simulation

The SMP began by examining the impact of single technologies on CO_2 emissions from road transport worldwide. Figure B-13 shows results for five such technologies—dieselization, hybridization, fuel cells, "carbon-neutral" hydrogen, and biofuels. It was assumed that each power train technology would achieve as close to 100 percent global sales penetration as possible given the characteristics of the technology and that each fuel would become as close to 100 percent of the global road transport fuel pool as its characteristics would permit.

The SMP emphasized that these single-technology examples were purely hypothetical. It is highly unlikely in practice that any single technology would achieve 100 percent penetration. Also, the examples cannot be added together. Differences in the timing of the implementation of these technologies and fuels in the developed and developing worlds were largely ignored.

For both diesels and advanced hybrids, it was assumed that 100 percent sales penetration would be reached by 2030 and that these technologies

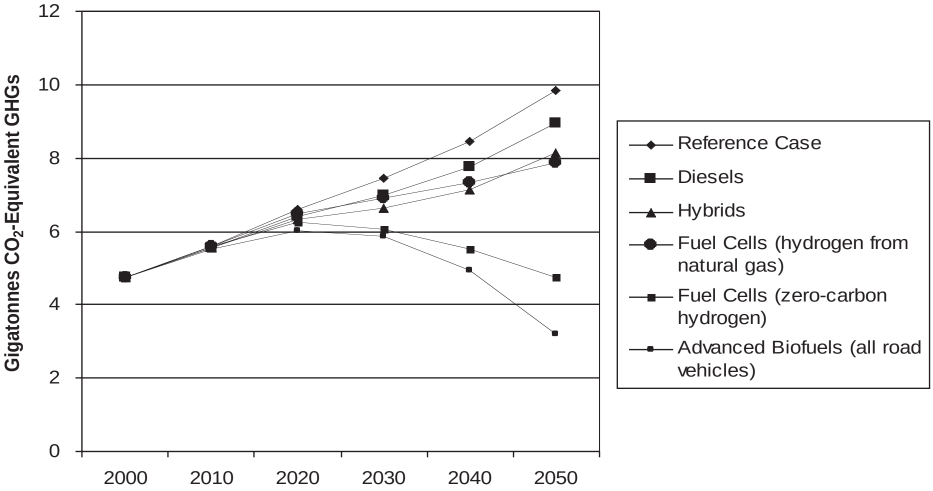


FIGURE B-13 **Hypothetical potential of individual technologies to lower road transport well-to-wheels GHG emissions relative to the SMP reference case.** (*Source:* World Business Council for Sustainable Development 2004, Figure 4.7, p. 113.)

would be used in LDVs and medium-duty trucks.[36] In the case of fuel cell vehicles, it was assumed that 100 percent sales penetration would be reached by 2050.[37] It was also assumed that the hydrogen used in these vehicles would be produced by reforming natural gas and that carbon sequestration would not be involved. The estimate of the impact of carbon-neutral hydrogen was generated by changing the WTT emissions characteristics of the hydrogen used in the fuel cell case just described. To focus on the impact of biofuels, it was assumed that these fuels would be used in a world road vehicle fleet similar in energy use characteristics to the SMP reference fleet. Diesel internal combustion engine technology (using conventional diesel fuel) was assumed to have an 18 percent fuel consumption benefit compared with the prevailing gasoline internal

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[36] A very high proportion of heavy trucks and buses are already diesel powered. The SMP assumed that hybrid technology would not see significant use in heavy-duty over-the-road trucks and buses because of their operating characteristics. Public transport buses are already being viewed as prime candidates for hybridization. These were not included in the SMP's calculation, but their omission makes relatively little difference in the results.

[37] The SMP made the same assumptions concerning the types of vehicles to which fuel cells might be applied as it did for hybrids.

combustion engine technology during the entire period. The fuel consumption benefit relative to gasoline internal combustion engine technology was assumed to be 36 percent for diesel hybrids, 30 percent for gasoline hybrids, and 45 percent for fuel cell vehicles.

From this single-technology assessment, it is evident that even if implemented worldwide, diesels and hybrid internal combustion engines fueled with conventional gasoline and diesel fuel or fuel cells fueled with natural gas–derived hydrogen could no more than slow the growth in road transport CO_2 emissions during the period 2000–2050. Only the use of carbon-neutral hydrogen in fuel cells and advanced biofuels in internal combustion engine–powered vehicles could largely or totally offset the increase in CO_2 emissions produced by the growth in road travel during the period 2000–2050.

This does not mean that vehicle energy use characteristics are irrelevant. They might not have a major impact on the trajectory of road vehicle GHG emissions over the very long term, but they would have a major impact on the amount of low-carbon or carbon-neutral fuel that would have to be produced to power the world's road vehicle fleet. This means they could have a very important impact on the cost of significantly reducing GHG emissions from road vehicles.[38]

On the basis of these results, the SMP concluded that it is only through a combination of fuel and power train solutions that significant CO_2 reduction can be attained. No single-technology pathway merits selection as the sole long-run solution.

Combined-Technology Simulation

Since the substantial reduction of CO_2 emissions from road vehicles is likely to depend on the widespread adoption of several advanced vehicle and fuel technologies, as well as other factors, the SMP decided to examine the combined impact of several actions, including the following:

- Fuels that are carbon neutral (defined by the SMP as ones that reduce WTW CO_2 emissions by at least 80 percent);
- Power trains that are highly energy efficient;

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[38] The fuel economy benefit relative to gasoline internal combustion engine technology was assumed to be 36 percent for diesel hybrids, 30 percent for gasoline hybrids, and 45 percent for fuel cell vehicles.

- A change in the historical mix-shifting trend to larger vehicle categories; and
- Improved traffic flow and other changes in transport activity resulting from better integration of transport systems, enabled, at least in part, by information technology.

The SMP set an illustrative target of reducing annual worldwide CO_2 emissions from road transport by half by 2050. This is equivalent to a decline in yearly CO_2 emissions of about 5 gigatonnes from levels that the SMP reference case projects would otherwise be reached and, by coincidence, returns annual road vehicle CO_2 emissions in 2050 to about their current levels.

For illustrative purposes, the CO_2 reduction target was divided into six increments. The timing and size of each increment are not fixed and ultimately would be decided on the basis of sustainability and investment choices at the national, regional, and global levels. The purpose of the analysis was to illustrate what might be achieved if ambitious changes were made beyond those in the SMP reference case, with no judgment as to cost or the probability of each step being taken.

Increment 1. Dieselization: It was assumed that dieselization of LDVs and medium-duty trucks would rise to around 45 percent globally by 2030 (that is, to about current European levels). Diesel engines were assumed to consume about 18 percent less fuel (and emit 18 percent less CO_2) than current gasoline internal combustion engines.

Increment 2. Hybridization: It was assumed that the hybridization (gasoline and diesel) of LDVs and medium-duty trucks would increase to half of all internal combustion engine vehicles sold by 2030. Gasoline hybrids were assumed to consume an average of 30 percent less fuel than current gasoline internal combustion engines, and diesel hybrids were assumed to consume an average of 24 percent less fuel than current diesels.[39]

Increment 3. Conventional and advanced biofuels: It was assumed that the quantity of biofuels in the total worldwide gasoline and diesel pool would rise steadily, reaching one-third by 2050. Conventional biofuels (those yielding a 20 percent CO_2 unit efficiency benefit) were capped at

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[39] It is generally acknowledged that, because of the diesel's initial superior energy efficiency, any additional benefit from hybridizing a diesel is likely to be smaller than that from hybridizing a gasoline engine.

5 percent of the total pool. The balance was assumed to be advanced biofuels (those yielding at least an 80 percent CO_2 unit efficiency benefit).[40]

Increment 4. Fuel cells using hydrogen derived from fossil fuels (no carbon sequestration): It was assumed that mass market sales of LDVs and medium-duty trucks would start in 2020 and rise to half of all vehicle sales by 2050. It also was assumed that fuel cell–equipped vehicles consume an average of 45 percent less energy than current gasoline internal combustion engines.

Increment 5. Carbon-neutral hydrogen used in fuel cells: It was assumed that hydrogen sourcing for fuel cells would switch to centralized production of carbon-neutral hydrogen over the period 2030–2050 once hydrogen LDV fleets had reached significant penetration at the country level. By 2050, 80 percent of hydrogen would be produced by carbon-neutral processes.

The first five increments reflect the inherent properties of different vehicle technologies and fuels. Actual reductions in CO_2 emissions will be determined not only by these properties but also by the mix of vehicles purchased by consumers and businesses and by how these vehicles are used on a daily basis. To reflect these two factors, two more increments were included.

Increment 6. Additional improvement in fleet-level vehicle energy efficiency: The SMP reference case projects an average improvement in the energy efficiency of the on-road LDV fleet of about 0.4 percent per year, with new vehicle sales showing an average 0.5 percent per year improvement in fuel economy. The improvement potential embodied in actual vehicles is around 1.0 percent per year, but about half of this potential improvement is offset because of vehicle purchasers' preferences for larger and heavy vehicles. In developing this increment, the SMP assumed that preferences relating to the mix of vehicles chosen by purchasers and the performance of these vehicles would change somewhat, leading to an additional 10 percent average annual in-use improvement relative to the reference case (i.e., average annual fleet-level improvement would rise from about 0.4 percent to about 0.6 percent).

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[40] This implies that these advanced biofuels are either gasoline from lignocellulosic sugar fermentation or diesel from biomass gasification/Fischer–Tropsch synthesis.

Increment 7. A 10 percent reduction in emissions due to better traffic flow and other efficiencies in road vehicle use: It was assumed that the gap between on-road energy-use performance and the technological improvements embodied in vehicles would narrow. How might this happen? For one thing, there are a number of opportunities relating to the increased use of information technology in transport systems that might enable the better management of travel demand. Improved routing information might permit trips to be shortened, while improved information about road conditions might reduce the amount of time motorists spend in their vehicles while idling in traffic. For another thing, more accurate and current information about when public transport vehicles will arrive and how long they will take to get to their destinations might encourage additional use of public transport. Individually, none of these improvements would be major, and almost certainly there would be offsets. But in combination, the SMP assumes that such factors could produce an additional 10 percent reduction in road vehicle CO_2 emissions.

Figure B-14 shows the results of the SMP combined-technologies analysis just described. It confirms the impression conveyed by the three single-technology analyses discussed above that the widespread adoption of a combination of vehicle and fuel technologies (plus other factors) would be required to return 2050 CO_2 emissions from road vehicles to their 2000 level.

SUMMARY

Any global warming that will be experienced during the next several decades will largely be the result of GHG emissions that have already occurred. As the main body of this report points out, regardless of what else it might do, America's transport sector will have to adjust to the consequences of this warming. But the transport sector in general, and America's transport sector in particular, is a significant source of GHG emissions. If future warming is to be limited, GHG concentrations in the atmosphere must be stabilized. This will require reducing GHG emissions not merely to below what they might otherwise be if present trends were to continue but to well below current levels. The transport sector will have to contribute to this reduction.

This appendix has identified several approaches by which transport-related GHG emissions might be reduced. A common characteristic of

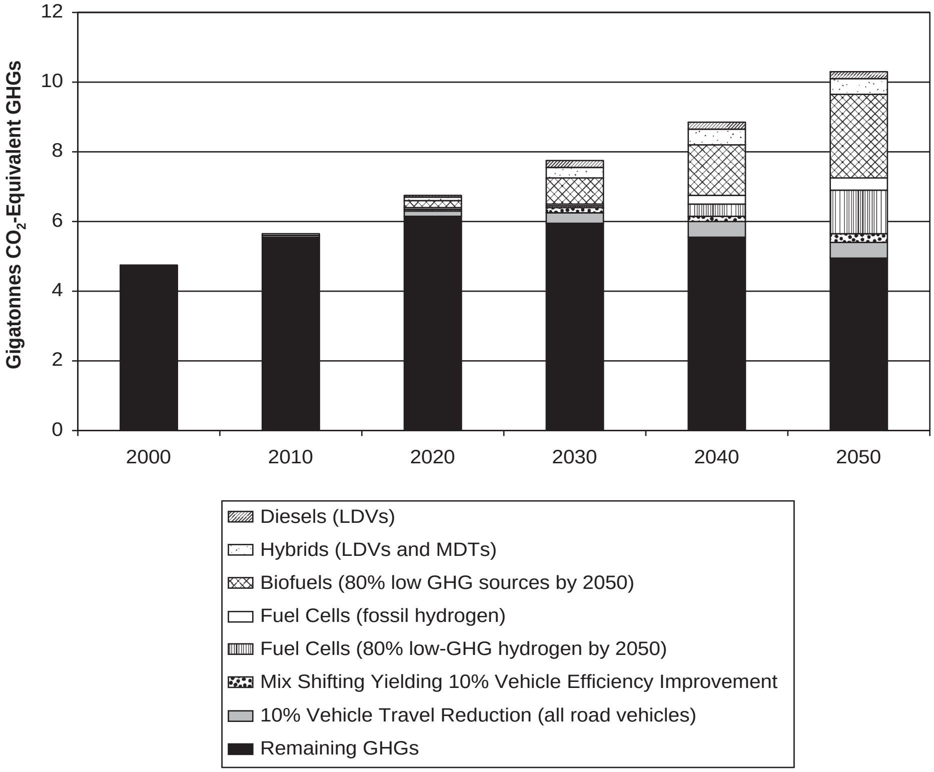

FIGURE B-14 **Combined-technology case.** (*Source:* Adapted from World Business Council for Sustainable Development 2004, Figure 4.11, p. 117.)

these approaches is that they take considerable time to be fully effective. This means that if transport-related GHG emissions are to be reduced to below their current levels by 2050, steps must be taken now to begin to implement certain of these approaches.

REFERENCES

Abbreviations

BTS	Bureau of Transportation Statistics
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
UN	United Nations

UNCTAD	United Nations Conference on Trade and Development
USEPA	United States Environmental Protection Agency
WBSCD	World Business Council on Sustainable Development

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APPENDIX C

Commissioned Papers and Authors

Case Study of the Transportation Sector's Response to and Recovery from Hurricanes Katrina and Rita. Lance R. Grenzeback and Andrew T. Lukmann, Cambridge Systematics, Inc., Jan. 10, 2007.

Climate Variability and Change with Implications for Transportation. Thomas C. Peterson, Marjorie McGuirk, Tamara G. Houston, Andrew H. Horvitz, National Oceanic and Atmospheric Administration, and Michael F. Wehner, Lawrence Berkeley National Laboratory, Dec. 6, 2006.

Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change. Michael D. Meyer, Georgia Institute of Technology, Dec. 18, 2006.

Operational Responses to Climate Change Impacts. Stephen C. Lockwood, PB Consult, Dec. 29, 2006.

Transportation Planning, Climate Change, and Decisionmaking Under Uncertainty. James A. Dewar and Martin Wachs, Dec. 13, 2006.

Note: The commissioned papers are available at www.trb.org/news/blurb_detail.asp?id=8808.

APPENDIX D

Conference Agenda and Participants

Conference on Climate Change Impacts on U.S. Transportation

Transportation Research Board
Division on Earth and Life Studies
National Research Council of the National Academies

Lecture Room
National Academy of Sciences Building
2100 C Street, NW, Washington, D.C.
October 12, 2006

AGENDA

8:30–8:45 a.m.	**Welcome, Overview of the Agenda, and Introduction to Paper Presentations** Henry G. Schwartz, Jr., Committee Chair
8:45–9:45 a.m.	**Current State of Knowledge on Climate Change and Implications for Transportation** Thomas R. Karl, moderator, committee member David J. Karoly, University of Oklahoma, presenter and discussant Thomas C. Peterson, Marjorie McGuirk, Tamara Houston, Andrew H. Horvitz, National Oceanic and Atmospheric Administration; and Michael F. Wehner, Lawrence Berkeley National Laboratory, paper authors General Discussion

9:45 a.m.–12:30 p.m.	**Adaptive Responses to Climate Change**
9:45–11:00 a.m.	**Reexamination of the Role of Transportation Design Standards in Light of Potential Impacts from Climate Change** Klaus H. Jacob, moderator, committee member Jonathan L. Gifford, George Mason University, presenter and discussant Michael D. Meyer, Georgia Institute of Technology, paper author
	General Discussion
11:00–11:15 a.m.	Break
11:15 a.m.–12:30 p.m.	**Operational Strategies to Address Climate Change** Alan C. Clark, moderator, committee member Michael M. Ryan, H. W. Lochner, Inc., presenter and discussant Stephen C. Lockwood, Parsons Brinckerhoff, paper author
	General Discussion
12:30–1:30 p.m.	Lunch break
1:30–2:45 p.m.	**Case Study of the Transportation Sector's Response to and Recovery from Hurricanes Katrina and Rita** George C. Eads, moderator, committee member Michael S. Bronzini, George Mason University, presenter and discussant Lance R. Grenzeback and Andrew Lukmann, Cambridge Systematics, Inc., paper authors
	General Discussion
2:45–3:00 p.m.	Break

3:00–4:15 p.m.	**Survey on Approaches to Decision Making Under Uncertainty** Robert J. Lempert, moderator, committee member Paul S. Fischbeck, Carnegie Mellon University, presenter and discussant James A. Dewar and Martin Wachs, paper authors General Discussion
4:15–5:00 p.m.	**Rapporteurs' Report and General Discussion** Henry G. Schwartz, Jr., moderator, Committee Chair Michael C. MacCracken, Climate Institute Thomas B. Deen, Transportation Research Board (retired)
5:00 p.m.	Adjourn

CONFERENCE PARTICIPANTS

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Great Lakes Commission

Lourdes Maurice
Federal Aviation Administration

Carol Murray
New Hampshire Department of Transportation

Gummada Murthy
Virginia Department of Transportation

Richard Nelson
Nevada Department of Transportation

George Newton
U.S. Arctic Research Commission

J. Rolf Olsen
Institute for Water Resources
U.S. Army Corps of Engineers

Harold Paul
Louisiana Transportation Research Center

William Petak
University of Southern California

Craig Philip
Ingram Barge Company

Britt Poole
ICF International, Inc.

Joanne Potter
Cambridge Systematics, Inc.

Ananth Prasad
Florida Department of Transportation

Stuart Price
RSVP Communications

David Robinson
Rutgers University

Craig Rockey
Association of American Railroads

Adam Rose
Pennsylvania State University

Eric Salathe
University of Washington

Michael Savonis
Federal Highway Administration

Leland Smithson
American Association of State Highway and Transportation Officials

Richard Somerville
Scripps Institution of Oceanography

Marty Spitzer
U.S. House of Representatives Committee on Science Subcommittee on the Environment, Technology, and Standards

Mark Stehly
Burlington Northern Santa Fe Railway

Laura Steinberg
Tulane University

Anne Sudar
Institute for Water Resources
U.S. Army Corps of Engineers

Megumi Sumitani
Seattle Office of City Auditor

Victoria Sutton
Research and Innovative Technology Administration

Anthony Taormina
Port of Hueneme

Kevin Wright
ICF International, Inc.

John Zamurs
New York State Department of Transportation

Rae Zimmerman
New York University

Jeffrey Zupan
Regional Plan Association

Study Committee Biographical Information

Henry G. Schwartz, Jr., *Chair,* is a nationally recognized civil and environmental engineering leader who spent most of his career with Sverdrup Civil, Inc. (now Jacobs Civil, Inc.), which he joined as a registered professional engineer in 1966. In 1993, Schwartz was named President and then Chairman, directing the transportation, public works, and environmental activities of Sverdrup/Jacobs Civil, Inc., before retiring in 2003. Dr. Schwartz's projects included multibillion-dollar water and wastewater treatment systems for the cities of San Diego, San Francisco, and Detroit, as well as large civil infrastructure projects, such as highways, bridges, dams, and railroads. Following his retirement, Dr. Schwartz was appointed Senior Professor and Director of the Engineering Management Program at Washington University in St. Louis, a position he held until fall 2006. He has served on the advisory boards for Carnegie Mellon University, Washington University, and the University of Texas, Austin, and is President of the Academy of Science of St. Louis. He is Founding Chairman of the Water Environment Research Foundation and has served as President of the Water Environment Federation. Dr. Schwartz is Past President of the American Society of Civil Engineers and was a member of the Civil Engineering Research Foundation Board of Directors. He was elected to the National Academy of Engineering in 1997 (Section 4: Civil Engineering) and has served on National Research Council (NRC) study committees, including the Committee for a Future Strategic Highway Research Program (SHRP), and on the NRC Board on Infrastructure and the Constructed Environment and the Executive Committee of the Transportation Research Board (TRB). Dr. Schwartz received a PhD from the California Institute of Technology and master of science and bachelor of science degrees from Washington University; he also attended Princeton University and Columbia University's business program.

Alan C. Clark is Director of the Houston–Galveston Area Council's (H-GAC's) metropolitan planning organization (MPO), which is responsible for development of the region's multimodal transportation plans and air quality programs. The MPO's Transportation Policy Council approves the programming of all federal highway and transit funds in Harris County and the seven adjacent counties. Mr. Clark's responsibilities also include coordinating the Houston–Galveston area's response to mandates contained in the Clean Air Act Amendments of 1990. He has been a transportation planner with H-GAC since 1983 and has managed its transportation and air quality programs since 1986. Mr. Clark has served as an Adjunct Professor with Texas Southern University. Before coming to H-GAC, he worked as a transportation planner with the Metropolitan Transit Authority of Harris County and as a traffic engineering consultant. He currently serves on the advisory councils of the Texas Transportation Institute and the Center for Transportation Training and Research at Texas Southern University. In 2006 he was appointed to the Federal Advisory Committee for the U.S. Climate Change Science Program study on the Impacts of Climate Variability and Change on Transportation Systems and Infrastructure—Gulf Coast Case Study. Mr. Clark holds master's degrees in civil engineering and in city and regional planning from Ohio State University. He completed his undergraduate degree in business administration at the University of Tennessee.

G. Edward Dickey is a consultant in water resources policy and planning; Senior Advisor providing policy, political, and technical advice and representation services on the planning and implementation of large-scale water projects at Dawson and Associates, a Washington-based representation firm; and Affiliate Professor of Economics at Loyola College in Maryland. He is former Chief of the Planning Division of the Headquarters Office of the U.S. Army Corps of Engineers and former Acting Assistant Secretary of the Army (Civil Works). Dr. Dickey has served on numerous NRC committees, including the Committee to Review the New York City Watershed Management Strategy, the Committee for the Study of Freight Transportation Capacity for the Next Century, and most recently the Panel on Adaptive Management for Resource Stewardship. He received PhD and master of art degrees in economics from Northwestern University and a bachelor of arts degree in political economy from the Johns Hopkins University.

George C. Eads is Senior Consultant at CRA International, Inc. [formerly Charles River Associates (CRA)] in its Washington, D.C., office. Before joining CRA in 1995, he held several positions at General Motors (GM) Corporation, including Vice President and Chief Economist; Vice President, Worldwide Economic and Market Analysis Staff; and Vice President, Product Planning and Economics Staff. Before joining GM, Dr. Eads was Dean of the School of Public Affairs at the University of Maryland, College Park, where he also was a professor. Before that, he served as a member of President Carter's Council of Economic Advisors. He has been involved in numerous projects concerning transport and energy. In 1994 and 1995 he was a member of President Clinton's policy dialogue on reducing greenhouse gas emissions from personal motor vehicles, popularly known as "Car Talk." He coauthored the World Energy Council's 1998 Report *Global Transport and Energy Development: The Scope for Change.* From 2000 to 2004, Dr. Eads devoted most of his time to the World Business Council for Sustainable Development's Sustainable Mobility Project, a project funded and carried out by 12 leading international automotive and energy companies. During the first stage of this project, he led the CRA contingent on the CRA–Massachusetts Institute of Technology team that together produced the project's first report, *Mobility 2001: World Mobility at the End of the Twentieth Century and Its Sustainability.* As lead consultant during the project's second and final phase, Dr. Eads drafted the project's final report, *Mobility 2030: Meeting the Challenges to Sustainability,* which was released in summer 2004 in Brussels, Detroit, and Tokyo. Dr. Eads is a member of the Presidents' Circle at the National Academies and has served on the Institute of Medicine's Committee on the Consequences of Uninsurance. He is an at-large Director of the National Bureau of Economic Research. He received a PhD in economics from Yale University.

Robert E. Gallamore is currently a private consultant, having recently retired as Director of the Transportation Center and Professor of Managerial Economics and Decision Sciences in the Kellogg School of Management, Northwestern University. Before joining the university in August 2001, he was an executive on loan from Union Pacific Railroad to the Transportation Technology Center in Pueblo, Colorado, where he was Assistant Vice President of Communications Technologies and General Manager of the North American Joint Positive Train Control Program.

He has also served in several positions with the federal government, including Deputy Federal Railroad Administrator and Associate Administrator for Planning of the Urban Mass Transportation Administration. Dr. Gallamore served as Chairman of the TRB Committee for a Study of the Feasibility of a Hazardous Materials Transportation Cooperative Research Program and the Committee on Freight Transportation Information Systems Security. He also served as a member of the TRB Committee for a Review of the National Transportation Science and Technology Strategy, the Steering Committee for a Conference on Railroad Research Needs, and the Transportation Panel of the Committee on Science and Technology for Countering Terrorism. Dr. Gallamore currently chairs the NRC Committee for Review of the Federal Railroad Administration Research and Development Program. He received a PhD in political economy and government from Harvard University.

Genevieve Giuliano is Senior Associate Dean of Research and Technology, Director of the METRANS Transportation Center, and Professor in the School of Policy, Planning, and Development at the University of Southern California. Dr. Giuliano's research interests include the relationship between land use and transportation, transportation policy evaluation, travel behavior, and the role of information technology in transportation. She has published more than 130 papers and reports and has presented her research at numerous conferences in the United States and abroad. She is currently a member of two international research consortia and serves on the editorial boards of several professional journals. She is a former member and chair of the TRB Executive Committee and a National Associate of the National Academies. Dr. Giuliano has served on several NRC and TRB policy study committees, including the Committee for the Study of Impacts of Highway Capacity Improvements on Air Quality and Energy Consumption; the Committee on Metropolitan Area Governance; the Committee on International Comparison of National Policies and Expectations Affecting Public Transit; the Committee for the Evaluation of the Congestion Mitigation and Air Quality Improvement Program; and the Committee on Transportation, Land Use, Physical Activity, and Health. She is currently chairing the TRB policy study Committee on Funding Options for Freight Transportation Projects of National Significance. Dr. Giuliano is also founding Chair of the California Transportation Research and

Technology Advisory Panel. She received a PhD in social sciences from the University of California at Irvine.

William J. Gutowski, Jr., is Professor of Meteorology in the Department of Geological and Atmospheric Sciences at Iowa State University. His research is focused on the role of atmospheric dynamics in climate, with emphasis on the dynamics of the hydrologic cycle and regional climate. Dr. Gutowski's research program entails a variety of modeling and data analysis approaches to capture the necessary spatial and temporal scales of these dynamics and involves working through the Regional Climate Modeling Laboratory at Iowa State University. His work also includes regional modeling of Arctic, African, and East Asian climates and involves collaboration with scientists in these regions. Dr. Gutowski received a PhD in meteorology from the Massachusetts Institute of Technology and a bachelor of science degree in astronomy and physics from Yale University.

Randell H. Iwasaki was appointed Chief Deputy Director of the California Department of Transportation (Caltrans) in November 2004. In that capacity, he manages the day-to-day operations of the department, including an operating budget of nearly $13 billion and more than 21,000 employees. A licensed civil engineer, Mr. Iwasaki has been with Caltrans for more than 20 years and has served as the department's Interim Director; Deputy Director for Maintenance and Operations; Director of Caltrans District 4, covering nine counties in the San Francisco Bay Area; and Director of Caltrans District 9, covering the eastern portion of the state. Mr. Iwasaki is a board member of the Intelligent Transportation Society of America, the Foundation for Pavement Preservation, and the Asian Pacific State Employee Association Foundation. He is chair of the SHRP 2 Technical Coordinating Committee for Renewal Research and serves on a TRB National Cooperative Highway Research Program panel on work zone safety. He was also recently appointed to the ITS Advisory Committee to Secretary Peters of the U.S. Department of Transportation. Mr. Iwasaki earned a bachelor's degree in engineering from California Polytechnic State University, San Luis Obispo, and a master's degree in environmental engineering from California State University, Fresno.

Klaus H. Jacob is Special Research Scientist at the Lamont–Doherty Earth Observatory of Columbia University, where he retired from a full-time position in 2001. He is also an Adjunct Professor at the School of International and Public Affairs at Columbia University, where he teaches disaster risk management. During the first two decades of his 36-year career with Columbia University, Dr. Jacob focused his research on basic earth physics and plate-tectonic processes. In 1986 he cofounded the National Science Foundation–supported National Center for Earthquake Engineering Research, where he worked on engineering and risk management applications for seismic hazards assessment and design criteria for large infrastructure projects. He has also worked intensively with federal, state, and local emergency management communities on risk mitigation strategies. Dr. Jacob's recent research efforts include studying how global climate change and related sea level rise affect the risks from coastal storm surges, flooding, and inundation, primarily of infrastructure systems. This research was applied in the recent Metropolitan East Coast Regional Assessment, which examined the impacts of climate change scenarios on the New York metropolitan area's transportation infrastructure, among other impact areas. Dr. Jacob has authored or coauthored more than 140 scientific and technical publications and book chapters. He is a member of the American Geophysical Union, the Seismological Society of America, the Earthquake Engineering Research Institute, the American Geological Institute, and the New York Academy of Sciences. Dr. Jacob holds a doctorate in geophysics from Goethe University (Frankfurt, Germany), a master of science degree in geophysics from Guttenberg University (Mainz), and a bachelor of science degree in mathematics and physics from the Technical University in Darmstadt.

Thomas R. Karl is Director of the National Climatic Data Center, a facility of the Commerce Department's National Oceanic and Atmospheric Administration, a position he has held since 1998. Before that, he was Senior Scientist at the climate center, where he analyzed global climate change, extreme weather events, and trends in global and U.S. climate over the past 100 years. Dr. Karl is a Fellow of the American Meteorological Society and the American Geophysical Union and past Chair of the Division on Earth and Life Sciences' Climate Research Committee. He has edited numerous journals, has authored more than 100 peer-reviewed journal articles, was lead author on several Intergovernmental Panel Assessments of climate change, and served as Cochair of the U.S. National Climate Assessment. In 2006 he was appointed to the Federal Advisory

Committee for the U.S. Climate Change Science Program study on the Impacts of Climate Variability and Change on Transportation Systems and Infrastructure—Gulf Coast Case Study. Dr. Karl received an honorary doctorate from North Carolina State University, a master's degree in meteorology from the University of Wisconsin, and a bachelor's degree from Northern Illinois University.

Robert J. Lempert is Senior Scientist at the Rand Corporation and an expert in science and technology policy, with a special focus on climate change, energy, and the environment. An internationally known scholar in the field of decision making under conditions of deep uncertainty, Dr. Lempert is a Fellow of the American Physical Society, a member of the National Academies' Climate Research Committee, and a member of the Council on Foreign Relations. Dr. Lempert is leading a National Science Foundation–funded study on the use of scientific and other information for climate change decision making under conditions of uncertainty. He has led studies on climate change policy, long-term policy analysis, and science and technology investment strategies for such clients as the White House Office of Science and Technology Policy, the U.S. Department of Energy, the National Science Foundation, and a variety of multinational firms. A Professor of Policy Analysis in the Rand Graduate School, Dr. Lempert teaches a course on complex adaptive systems and policy analysis. He authored the book *Shaping the Next One Hundred Years: New Methods for Quantitative, Longer-Term Policy Analysis.* Dr. Lempert holds a PhD in applied physics from Harvard University and a BAS degree in physics and political science from Stanford University.

Luisa M. Paiewonsky is Commissioner of the Massachusetts Highway (MassHighway) Department, where she oversees a combined annual capital and operating budget of $890 million, manages 1,850 employees, and has responsibility for more than 9,500 lane miles of roadway and 2,800 bridges. Before her appointment as Commissioner in 2005, Ms. Paiewonsky served as Assistant Secretary of the Executive Office of Transportation and before that as Deputy Commissioner of MassHighway, responsible for the day-to-day operations of the commonwealth's road and bridge program. Ms. Paiewonsky rose through the MassHighway ranks with a series of promotions that included a 4-year term as Director of the Bureau of Transportation Planning and Development and Project

Manager for the $35 million Southeast Expressway High-Occupancy Vehicle (HOV) project. She spearheaded MassHighway's participation in the development of the Anderson Regional Transportation Center, built on a former Superfund site. Ms. Paiewonsky is President of the Boston Chapter of the Women's Transportation Seminar and a member of the Northeast Association of State Highway and Transportation Officials. She serves as a Massachusetts representative to TRB and is secretary of TRB's HOV Systems Committee. Ms. Paiewonsky graduated from Mount Holyoke College with a bachelor's degree in political science and Spanish. She holds a master's degree in city planning from Boston University.

Christopher R. Zeppie is Director of the Office of Environmental Policy, Programs, and Compliance at the Port Authority of New York and New Jersey. Since coming to the Port Authority in 1979, Mr. Zeppie has held positions of increasing responsibility as Environmental Compliance Specialist; Manager, Permits and Governmental Approvals; Attorney, Environmental Law Division; Assistant Director, Office of Environmental Management; and Chief Environmental Policy Officer. He is a member of the Dean's Council at the State University of New York at Stony Brook's School of Marine and Atmosphere Studies, the Advisory Committee of the Environmental Division of the New York Academy of Sciences, the Review Panel for the Stony Brook Storm Surge Research Group Investigation of the Hydrologic Feasibility of Storm Surge Barriers to Protect the Metropolitan New York–New Jersey Region, and a Stakeholder Partner of the Infrastructure Group for the Metropolitan East Coast Regional Assessment. Mr. Zeppie was appointed by Mayor Bloomberg to serve on the Jamaica Bay Watershed Advisory Committee and will be representing the Port of New York and New Jersey as a delegate to the C40 Conference working group on Port Facilities in Rotterdam. He holds a bachelor of science degree in biology and ecology from Manhattan College, a master's degree in marine environmental science from State University of New York at Stony Brook, and a JD degree from St. John's University School of Law.