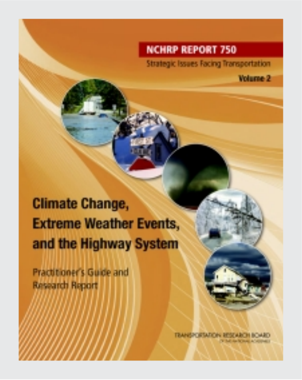

Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report

DETAILS

204 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-28378-6 | DOI 10.17226/22473

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 750

Strategic Issues Facing Transportation

Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report

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Subscriber Categories
Design • Highways • Planning and Forecasting

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2014
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 750, VOLUME 2

Project 20-83(5)
ISSN 0077-5614
ISBN 978-0-309-28378-6
Library of Congress Control Number 2013932452

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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http://www.national-academies.org/trb/bookstore

Printed in the United States of America

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FOREWORD

By Edward T. Harrigan
Staff Officer
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Major trends affecting the future of the United States and the world will dramatically reshape transportation priorities and needs. The American Association of State Highway and Transportation Officials established the NCHRP Project 20-83 research series to examine global and domestic long-range strategic issues and their implications for departments of transportation (DOTs) to help prepare the DOTs for the challenges and benefits created by these trends. *NCHRP Report 750: Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report* is the second report in this series.

This report presents guidance on adaptation strategies to likely impacts of climate change through 2050 in the planning, design, construction, operation, and maintenance of infrastructure assets in the United States (and through 2100 for sea-level rise).

There are many potential impacts of climate change on the highway system. Climate change is likely to increase the Earth's average temperature, change extreme temperatures in different parts of the world, raise sea levels, and alter precipitation patterns and the incidence and severity of storms. Such change will likely become an important driver of how the state departments of transportation (DOTs) design, plan, construct, operate, and maintain their highway systems. Recent extreme weather events, such as Hurricanes Katrina and Sandy, and massive flooding in the Northwest and Midwest states, have led to a rethinking of how infrastructure is designed and managed during such events.

Practitioners need a sound foundation on which to plan for the near-term—through 2050—impacts of climate change. This foundation should encompass an assessment of the probable impacts, identification of vulnerable infrastructure, and technical tools and proposed institutional arrangements to guide adaptation of the infrastructure to the anticipated impacts.

The objectives of NCHRP Project 20-83(05) were to (1) synthesize the current state of worldwide knowledge regarding the probable range of impacts of climate change on highway systems by region of the United States for the period 2030–2050; (2) recommend institutional arrangements, tools, approaches, and strategies that state DOTs can use to adapt infrastructure and operations to these impacts and lessen their effects; and (3) identify future research and activities needed to close gaps in current knowledge and implement effective adaptive management. The research was conducted by Parsons Brinckerhoff (Washington, D.C.) in association with Cambridge Systematics (Cambridge, Massachusetts) and Stratus Consulting (Boulder, Colorado).

The project examined adaptation to climate change on three scales of application—road segment, corridor, and network—including the types of impacts likely to be faced in coming years and the different design, operations, and maintenance strategies that can be considered. The report discusses adaptation planning in the United States and in other countries, with special consideration for the approaches taken in developing adaptation strategies. A diagnostic framework for adaptation assessment is presented consisting of eight steps:

1. Identify key goals and performance measures for the adaptation planning effort.
2. Define policies on assets, asset types, or locations that will receive adaptation consideration.
3. Identify climate changes and effects on local environmental conditions.
4. Identify the vulnerabilities of asset(s) to changing environmental conditions.
5. Conduct risk appraisal of asset(s) given vulnerabilities.
6. Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness, and defensibility of options.
7. Coordinate agency functions for adaptation program implementation (and optionally identify agency/public risk tolerance and set trigger thresholds).
8. Conduct site analysis or modify design standards (using engineering judgment), operating strategies, maintenance strategies, and construction practices.

This volume assembles two major project deliverables:

- The Practitioner’s Guide (Part I) to conducting adaptation planning from the present through 2050 (through 2100 for sea-level rise)
- The research report (Part II) that summarizes the research results supporting the development of the Practitioner’s Guide and provides recommendations for future research.

Three other project deliverables are available on the accompanying CD-ROM and on the TRB website (http://www.trb.org/Main/Blurbs/169781.aspx):

- A software tool that runs in common web browsers and provides specific, region-based information on incorporating climate change adaptation into the planning and design of bridges, culverts, stormwater infrastructure, slopes, walls, and pavements.
- Tables that provide the same information as the previously mentioned software tool, but in a spreadsheet format that can be printed.
- Two spreadsheets that illustrate examples of the benefit–cost analysis of adaptation strategies discussed in Appendix B of Part I.

CONTENTS

PART I Practitioner's Guide

PART II Research Report

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

PART I

Practitioner’s Guide

SUMMARY

Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide

Extreme weather events, hurricanes, tropical storms, and prolonged intense temperatures have heightened awareness of a changing climate. Even for those who are skeptical about the long-term effects of this change, there is strong evidence to suggest that these extreme weather events are occurring more frequently, with the need for state transportation agencies to respond to the aftermath. Over the longer term, the latest climate modeling projects the climate to change at an increasingly rapid pace over the coming decades. Such change will likely alter both long-term climatic averages and the frequency and severity of extreme weather events, both of which play an important role in the planning, design, operations, maintenance, and management of highways.

Projected climate and weather changes will have important implications for the long-term safety and functionality of the highway system. This guide was developed to help transportation professionals understand the changes in climate that may affect the future (and, in the case of extreme weather events, the current) transportation system and how assets and activities can be adapted to provide transportation system resiliency in the face of changing environmental conditions.

In this guide "adaptation" consists of actions to reduce the vulnerability of natural and human systems or to increase system resiliency in light of expected climate change or extreme weather events.

The guide is organized to show how adaptation can be considered within the context of agency activities. A diagnostic framework for undertaking an adaptation assessment is presented and provides the basic organization of the guide. This framework includes the steps that should be taken if transportation officials want to know what climate stresses the transportation system might face in the future; how vulnerable the system will likely be to these stresses; and what strategies can be considered to avoid, minimize, or mitigate potential consequences. How adaptation concerns can be incorporated into a typical transportation planning process is also described.

The eight-step diagnostic framework is as follows:

Step 1: Identify key goals and performance measures for the adaptation planning effort.
Step 2: Define policies on assets, asset types, or locations that will receive adaptation consideration.
Step 3: Identify climate changes and effects on local environmental conditions.
Step 4: Identify the vulnerabilities of asset(s) to changing environmental conditions.
Step 5: Conduct risk appraisal of asset(s) given vulnerabilities.
Step 6: Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness, and defensibility of options.

Step 7: Coordinate agency functions for adaptation program implementation (and optionally identify agency/public risk tolerance and set trigger thresholds).
Step 8: Conduct site analysis or modify design standards (using engineering judgment), operating strategies, maintenance strategies, construction practices, etc.

Climate "stressors" are characteristics of the climate—such as average temperature, temperature ranges, average and seasonal precipitation, and extreme weather events—that could in some way affect the design, construction, maintenance, and operations of a transportation system or facility. Preliminary experience with adaptation planning from around the world indicates that this initial step of identifying expected stressors varies in sophistication from the use of expert panels to large-scale climate modeling. Key conclusions relating to climate stressors presented in the guide include the following:

- Temperatures in the lower 48 states are projected to increase about 2.3°C (4.1°F) by 2050 relative to 2010.
- While all U.S. regions are projected to increase in temperature, the amounts will vary by location and season. In general, areas farther inland will warm more than coastal areas, because the relatively cooler oceans will moderate the warming over coastal regions. In addition, northern areas will warm more than southern areas because there will be less high-latitude snow cover to reflect sunlight. More warming is projected for northern and interior regions in the lower 48 states than for coastal and southern regions.
- In general, the models project, and observations show, that the Northeast and Midwest are likely to become wetter while the Southwest is likely to become drier. In addition, all the climate models project an increase in precipitation in Alaska. It is unknown whether precipitation will increase in other areas such as the Northwest or the Southeast.
- While the models tend to show a drier Southwest and a wetter Northeast and Midwest, the differences across the models mean it is not possible to forecast exactly which localities become wetter or drier nor where the transitions between wet and dry areas lie.
- Climate models tend to project relatively wetter winters and drier summers across most of the United States. However, this does not mean that all areas are projected to receive more precipitation in the winter and less precipitation in the summer. The models also project a larger increase in summer temperature than winter temperature.
- Extreme temperatures will get higher. This means that all locations will see increases in the frequency and duration of occurrence of what are now considered extreme temperatures such as days above 32°C (90°F) or 35°C (95°F).
- In the long run, the number of days below freezing will decrease in many areas, particularly southern locations.
- Precipitation intensities (both daily and 5-day) are projected to increase almost everywhere, although the largest increases tend to happen in more northern latitudes.
- Recent research has suggested that there could be fewer hurricanes, but the ones that do occur, particularly the most powerful ones, will be even stronger.
- Global sea levels are rising. Projections of future sea-level rise vary widely. The Intergovernmental Panel on Climate Change (IPCC) projects that sea level will rise 8 inches to 2 feet (0.2 to 0.6 meters) by 2100 relative to 1990. Several studies published since the IPCC Fourth Assessment Report, however, estimate that sea levels could rise 5 to 6.5 feet (1.5 to 2 meters) by 2100.
- Sea-level rise seen at specific coastal locations can vary considerably from place to place and from the global mean rise because of differences in ocean temperatures, salinity, and currents—and because of the subsidence or uplift of the coast itself.

The approach used in any particular adaptation effort will most likely relate to the available budget, the availability of climate change projections from other sources (e.g., a university), and the overall goal of the study. The main tools used to simulate global climate and the effects of increased levels of greenhouse gases (GHGs) are called "general circulation models" (GCMs). The guide provides advice on how to use climate models and model output:

- A range of emission scenarios should be used to capture a reasonable range of uncertainty about future climate conditions.
- It generally does not make sense to use outputs from climate models to project climate less than three decades from now. For these shorter timescales, historical climate information averaged over recent decades can be used. To get estimates of how climate more than two to three decades from now may change, climate models should be used.
- Beyond 2050, it may be prudent to use more than one emissions scenario if possible. An important reason for using a wide range of emissions scenarios is to find out how a system could be affected by different magnitudes of climate change.
- Climate models project future climate on a sub-daily basis. Using sub-daily data, even daily data, is very complicated. To make things much easier, typically average monthly changes in variables, such as temperature and precipitation, from the models are used.
- It is not advisable to use just one climate model. For a given emissions scenario, a model only gives one projection of change in climate, which can be misinterpreted as a forecast. That can be particularly misleading given the uncertainties about regional climate change.
- Model quality can be assessed in two ways: by examining how well the model simulates current (observed) climate and by determining whether the model's projections are consistent with other models. Models that simulate current climate poorly or that give projections that differ strikingly (not by a relatively small amount) from all other models (i.e., "outliers") should probably be eliminated from consideration.

The guide identifies likely impacts on the highway system, shown in Table I.1, and in addition presents different strategies that can be used to minimize or avoid climate change–related disruptions.

An asset is *vulnerable* to climatic conditions if conditions such as intense precipitation and extreme temperatures and their aftermath (e.g., a flood exceeding certain stages and consecutive days of higher than 100°F temperatures) result in asset failure or sufficient damage to reduce asset functionality. Climate-related *risk* is more broadly defined; it relates to not only the failure of that asset but also the consequences or magnitudes of costs associated with that failure (Willows and Connell 2003). In this case, a consequence might be the direct replacement costs of the asset; direct and indirect costs to asset users; and, even more broadly, the economic costs to society given the disruption to transportation caused by failure of the asset or even temporary loss of its services (e.g., a road is unusable when it is under water).

The complete risk equation is thus:

$$\begin{aligned}\textit{Risk} = {} & \textit{Probability of Climate Event Occurrence} \times \textit{Probability of Asset Failure} \\ & \times \textit{Consequence or Costs}\end{aligned}$$

From a practical perspective, knowing whether the location and/or design of the facility presents a high level of risk to disruption due to future climate change is an important part of the design decision. For existing infrastructure, identifying high-risk assets or locations provides decision makers with some sense of whether additional funds should be spent to lower future climate change–related risk when reconstruction or rehabilitation occurs. This could include conducting an engineering assessment of critical assets that might be vulnerable to climate stressors. This approach, in essence, "piggybacks" adaptation strategies on top of other program functions (e.g., maintenance, rehabilitation, reconstruction, etc.).

Table I.1. Summary of climate change impacts on the highway system.

Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
Temperature		
Change in extreme maximum temperature	• Premature deterioration of infrastructure. • Damage to roads from buckling and rutting. • Bridges subject to extra stresses through thermal expansion and increased movement.	• Safety concerns for highway workers limiting construction activities. • Thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs. • Vehicle overheating and increased risk of tire blowouts. • Rising transportation costs (increase need for refrigeration). • Materials and load restrictions can limit transportation operations. • Closure of roads because of increased wildfires.
Change in range of maximum and minimum temperature	• Shorter snow and ice season. • Reduced frost heave and road damage. • Later freeze and earlier thaw of structures because of shorter freeze-season lengths • Increased freeze–thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces. • Increased slope instability, landslides, and shoreline erosion from permafrost thawing leads to damaging roads and bridges due to foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost). • Hotter summers in Alaska lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.	• Decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, and result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles. • Longer road construction season in colder locations. • Vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons). • Roadways built on permafrost likely to be damaged due to lateral spreading and settlement of road embankments. • Shorter season for ice roads.
Precipitation		
Greater changes in precipitation levels	• If more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction. • Increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration). • Less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode. • Road embankments could be at risk of subsidence/heave. • Subsurface soils may shrink because of drought.	• Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents). • Roadways and underground tunnels could close due to flooding and mudslides in areas deforested by wildfires. • Increased wildfires during droughts could threaten roads directly or cause road closures due to fire threat or reduced visibility. • Clay subsurfaces for pavement could expand or contract in prolonged precipitation or drought, causing pavement heave or cracking.

Table I.1. (Continued).

Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
Increased intense precipitation, other change in storm intensity (except hurricanes)	• Heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting), which could lead to permanent road closures. • Heavy precipitation and increased runoff can cause damage to tunnels, culverts, roads in or near flood zones, and coastal highways. • Bridges are more prone to extreme wind events and scouring from higher stream runoff. • Bridges, signs, overhead cables, and tall structures could be at risk from increased wind speeds.	• The number of road closures due to flooding and washouts will likely rise. • Erosion will occur at road construction project sites as heavy rain events take place more frequently. • Road construction activities could be disrupted. • Increases in weather-related highway accidents, delays, and traffic disruptions are likely. • Increases in landslides, closures or major disruptions of roads, emergency evacuations, and travel delays are likely. • Increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/maneuverability, lane obstruction (debris), and treatment chemical dispersion. • Lightning/electrical disturbance could disrupt transportation electronic infrastructure and signaling, pose risk to personnel, and delay maintenance activity.
Sea Level		
Sea-level rise	• Erosion of coastal road base and undermining of bridge supports due to higher sea levels and storm surges. • Temporary and permanent flooding of roads and tunnels due to rising sea levels. • Encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events). • Further coastal erosion due to the loss of coastal wetlands and barrier islands removing natural protection from wave action.	• Coastal road flooding and damage resulting from sea-level rise and storm surge. • Increased exposure to storm surges. • More frequent and severe flooding of underground tunnels and other low-lying infrastructure.
Hurricanes		
Increased hurricane intensity	• Increased infrastructure damage and failure (highway and bridge decks being displaced).	• More frequent flooding of coastal roads. • More transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods). • More coastal evacuations.

The guide recommends how adaptation considerations can be incorporated into environmental analysis and engineering design. For environmental analysis, the guide recommends five questions that should be answered in the context of an environmental study:

1. What *climate stressors* will affect the proposed action either directly or through effects on the surrounding ecology?
2. What are the *impacts of these stressors on the affected environment* for the proposed action (and to what extent is any proposed action in an area vulnerable to climate change)?

3. What is the *risk to the asset and to the affected environment* given expected changing climatic conditions?
4. To what extent do these stressors *influence the desired characteristics of the proposed action* (e.g., efforts to avoid, minimize, or mitigate potential risks)?
5. What are the *recommended strategies for protecting the function and purpose* of the proposed action?

The guide discusses how engineers can adapt their practices to a constantly changing climate. A set of tables are presented that shows how adaptation can be incorporated into the planning and design of specific asset types. Detailed tables include specific guidance for bridges, culverts, stormwater infrastructure, slopes/walls, and pavement. The guide also includes in Appendix B a benefit–cost approach for determining whether a particular adaptation strategy is worth investing in today given the risk climate change poses in future years.

Finally, the guide discusses how adaptation concerns can be linked to the construction, operations and management, and asset management activities of an agency. It is expected that over time construction programs will adapt to changes in climate through the following actions:

- Changes to the windows available for certain weather-sensitive construction activities (e.g., paving) including, in many cases, a lengthening of the construction season
- Changes in working hours or other strategies to protect laborers from heat waves
- Different types of materials and designs being used (this is not a threat though because in most cases there will be time to produce more temperature- and rain-resistant materials)
- Enhanced erosion and sedimentation control plans to address more extreme precipitation events
- Greater precautions in securing loose objects on job sites or new tree plantings that may be affected by stronger winds

Extreme weather events, however, will likely be of great concern to contractors and owner agencies.

With respect to network operations, several types of strategies will likely be considered, including the following:

- Improvements in *surveillance and monitoring* must exploit a range of potential weather-sensing resources—field, mobile, and remote.
- With improved weather information, the more sophisticated archival data and integration of macro and micro trends will enable regional agencies to *improve prediction* and prepare for long-term trends.
- These improvements in turn can support the development of effective *decision support technology* with analyses and related research on needed treatment and control approaches.
- The objective to be pursued would be road operational regimes for *special extreme weather-related strategie*s such as evacuation, detour, closings, or limitations based on *preprogrammed routines*, updated with *real-time information* on micro weather and traffic conditions.
- For such strategies to be fully effective, improved *information dissemination* will be essential—both among agencies and with the public, using a variety of media.
- The *institutionalization* of the ability to conduct such advanced operations will depend on important changes in *transportation organization* and staff capacity as well as new, more *integrated interagency relationships.*

For maintenance, it is important for maintenance management systems to prioritize needs and carefully meter out resources so as to achieve maximum long-term effectiveness.

Climate change and the associated increase in extreme weather is an increasingly important factor in this estimation. With respect to culverts, for example, as increasing financial, regulatory, and demand maintenance factors make it increasingly difficult to inspect and maintain culverts, the increasing risks due to climate change are exacerbated. The remedy is to provide additional resources for culvert management, repair, and retrofit; however, this is often beyond the capacity of an overcommitted maintenance budget.

Asset management systems also rely on periodic data collection on a wide range of data, most importantly on asset condition, and thus serve as an already established agency process for monitoring what is happening to agency assets. Some of the more sophisticated asset management systems have condition deterioration functions that link expected future asset conditions to such things as traffic volumes and assumed weather conditions, thus providing an opportunity to relate changing climate and weather conditions to individual assets. One of the most valuable roles an asset management system could have for an agency is its continuous monitoring of asset performance and condition. This represents a ready-made platform that is already institutionalized in most transportation agencies, and significant resources would not be required to modify its current structure to serve as a climate change resource to the agency.

Finally, the guide highlights the need for collaboration with other agencies and jurisdictions and the benefits of such collaboration described. This collaboration is needed not only with environmental resource agencies but also with local agencies responsible for local roads and streets whose condition and performance can affect higher level highways. As noted in the guide, one of the most important collaborations could be with land use planning agencies where, for particularly vulnerable areas, the best strategy might be to avoid development from occurring in the first place.

CHAPTER 1

Introduction and Purpose

Why Is This Guide Needed?

The climate is changing and, according to the latest climate modeling, is projected to continue changing at an increasingly rapid pace over the coming decades. Although reducing greenhouse gas (GHG) emissions offers an opportunity to dampen this trend, some degree of climate change is inevitable given the vast amounts of greenhouse gases already released and their long life span in the atmosphere. Such change will likely alter long-term climatic averages and the frequency and severity of extreme weather events, all of which play an important role in the planning, design, operations, maintenance, and management of highways (Meyer et al. 2012a). Projected climate and weather changes will have important implications for the long-term safety and functionality of the highway system. Extreme weather events are also likely to be much more an issue to many state transportation agencies in the future (Lubchenco and Karl 2012; Coumou and Rahmstorf, 2012).

This guide was developed to help transportation professionals understand the changes in climate that may affect the future (and, in the case of extreme weather events, the current) transportation system and how assets and activities can be adapted to provide transportation system resiliency in the face of changing environmental conditions.

In many ways, climate change presents a fundamental challenge to engineering and planning practice given that transportation infrastructure has traditionally been planned and designed based upon historical climate data under the implicit assumption that the climate is static and the future will be like the past. Climate change challenges this assumption and suggests that transportation professionals might need to consider new kinds of risks in facility design and system operations. This will be no easy task given the inherent uncertainties in any projections of the future, the patchwork climate projections available in the United States, and the inertia behind current practice. However, changes might be needed if transportation professionals are to deliver cost-effective and resilient transportation infrastructure.

Adapting infrastructure to better withstand these impacts could allow infrastructure to remain operational through extreme weather events that otherwise would result in failure. Adaptations may also help to reduce operations and maintenance costs, improve safety for travelers, and protect the large investments made in transportation system infrastructure. This guide is intended (1) to help transportation professionals identify how their work could be affected by the consideration of climate change and extreme weather events and (2) to provide guidance on how to account for such changes. Guidance on incorporating adaptations into operations and maintenance practices, construction activities, and the planning and (re)design of new and existing infrastructure is detailed within this guide. Before getting into these details, however, it is important to understand what is meant by "adaptation."

What Is Adaptation?

A number of organizations have sought to define the concept of adaptation. For purposes of this guide:

> Adaptation consists of actions to reduce the vulnerability of natural and human systems or to increase system resiliency in light of expected climate change or extreme weather events.

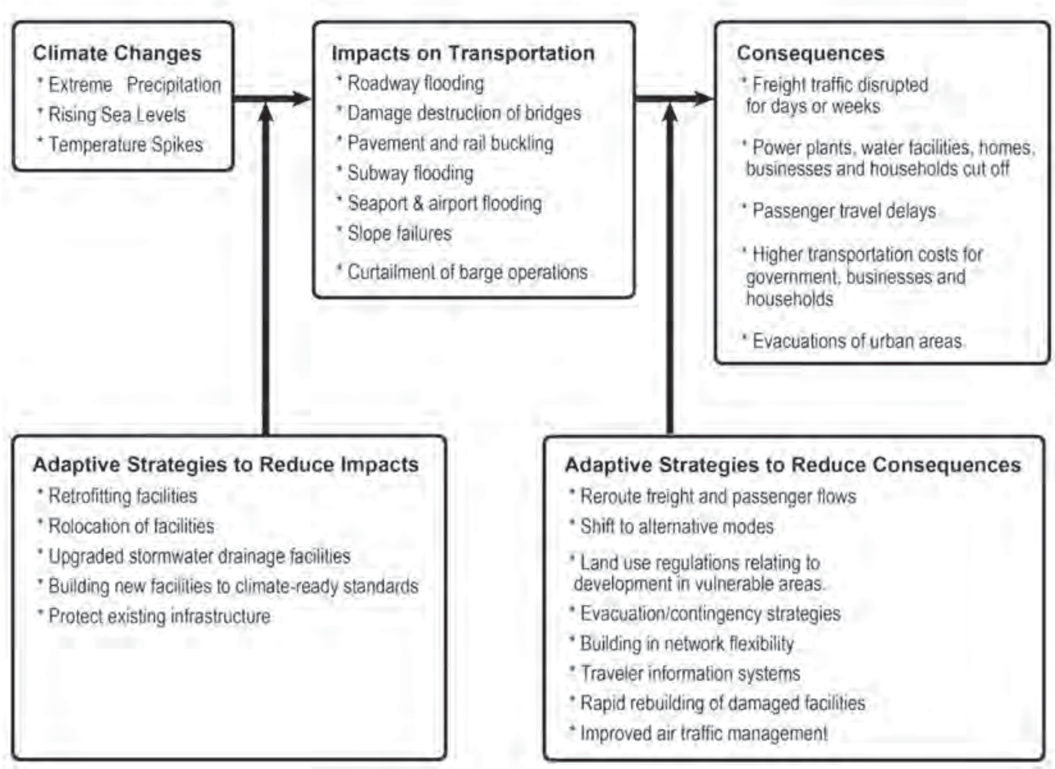
Several aspects of this definition merit attention. First, the types of actions that can be taken to reduce vulnerability to changing environmental conditions could include *avoiding*, *withstanding*, and/or *taking advantage of* climate variability and impacts. Thus, for roads and other transportation facilities, *avoiding* areas projected to have a higher risk of potentially significant climate impacts should be an important factor in planning decisions. If such locations cannot be avoided, steps need to be taken to ensure that the transportation infrastructure can *withstand* the projected changes in environmental conditions. For example, the potential for increased flooding might be a reason to increase bridge elevations beyond what historic data might suggest. Climate change may also present *opportunities* that transportation professionals can take advantage of, for example, lower snow removal costs in some locations.

Second, the result of adaptive action either decreases a system's vulnerability to changed conditions or increases its resilience to negative impacts. For example, increasing temperatures can cause pavements on the highway system to fail sooner than anticipated. Using different materials or different approaches that recognize this vulnerability can lead to pavements that will survive higher temperatures.

With respect to resiliency, operations improvements could be made to enhance detour routes around flood-prone areas. Another example of resiliency is well-designed emergency response plans, which can increase resiliency by quickly providing information and travel alternatives when highway facilities are closed and by facilitating rapid restoration of damaged facilities. By increasing system resiliency, even though a particular facility might be disrupted, the highway network as a whole still functions.

Figure I.1 shows different contexts for adaptation. Some adaptation strategies could be targeted to reduce the impacts of specific types of climate changes. For example, by protecting existing assets or by relocating assets away from vulnerable areas, the functionality of that asset is preserved in future years when more extreme weather events could create a threat. The second type of adaptation strategy aims to reduce or mitigate the consequences of the impacts to transportation given that the climate impacts have occurred. In this case, the focus of adaptation is preserving human life, minimizing economic impact, and replacing damaged infrastructure as quickly as possible.

Ultimately, a wide range of activities can be considered "adaptation," from relatively simple operations and maintenance actions such as ensuring culverts are clear of debris to complex and costly planning and engineering actions like re-locating a road alignment away from a flood-prone area. Given the broad scope of adaptation activities, it is important that a comprehensive decision-making approach be formulated that describes the steps engineers, planners, operations and maintenance personnel, and other highway officials can take to assess the range of climate change impacts on the transportation system as a whole and avoid piecemeal decision making. Such an approach should also be sufficiently flexible to allow for the consideration of updated climate change forecasts as well as an examination of a range of potential cost-effective solutions.



Source: National Climate Assessment working group on climate-related transportation impacts, May 2012. Printed with permission.

Figure I.1. Adaptation strategies and their role in reducing impacts and the consequences of impacts.

Who Should Read What?

This guide is organized to allow readers to focus on the adaptation issues of most interest. Thus, for agencies that have already obtained climate data that can be used for adaptation planning purposes, the chapter on climate change data and modeling (Chapter 3) might not be that useful (although it does provide observations on the limitations of such data and on their use within an adaptation planning effort). Those new to climate adaptation should read the guide in its entirety.

The remainder of the guide is as follows:

- Chapter 2 provides an organizing diagnostic framework for undertaking an adaptation assessment. This framework includes the steps that should be taken if transportation officials want to know what climate stresses the transportation system might face in the future; how vulnerable the system will likely be to these stresses; and what strategies can be considered to avoid, minimize, or mitigate potential consequences. This chapter also describes how adaptation concerns can be incorporated into a typical transportation planning process.
- Chapter 3 provides a tutorial on the basics of climate change modeling and model results for those unfamiliar with such approaches. This chapter also provides sources of data and information on climate change that readers can use for their own study purposes.
- Chapter 4 then presents information on the likely impacts of different climate stressors on the highway system, and the types of strategies that can be considered as part of an agency's adaptation efforts. Those who have not yet thought of what climate change means to their agency will find this section most useful.

- Chapter 5 presents approaches and methods for considering the risk to infrastructure of changing climatic conditions and extreme weather events, one of the key challenges in adaptation planning. Risk to infrastructure has been repeatedly identified by practitioners as one of the most difficult tasks in adaptation planning.
- Chapter 6 focuses on what adaptation might mean to the project development process. An example on culvert design leads the reader through a decision support approach that provides options in the context of expected changes in climatic conditions. In addition, this chapter provides some useful suggestions on how to incorporate adaptation into environmental analysis.
- Chapter 7 discusses how to institutionalize adaptation into targeted agency functions. This includes not only the more immediate concern with construction, operations, and maintenance (such as in response to extreme weather events), but also the more systematic monitoring effort as found in asset management systems.
- Appendix A presents sea-level rise projections for the nation's coastal states for the years 2050 and 2100.
- Appendix B presents a benefit–cost methodology that can be used for identifying the most beneficial (from a monetary perspective) adaptation alternative.
- The CD-ROM contains the spreadsheet-based tables and web-browser-based decision support tool that show how adaptation can be incorporated into the planning and design of specific asset types and examples of the benefit–cost analysis discussed in Appendix B.

CHAPTER 2

Framework for Adaptation Planning and Strategy Identification

How should a transportation agency assess and adapt to the challenges of climate change? This question is becoming more important as extreme weather events occur more frequently and more transportation agencies come to believe that these events go beyond normal climate variability. A diagnostic framework for addressing climate change and adaptation of the highway system is presented in this chapter. The diagnostic framework provides highway agency staff with a general step-by-step approach for assessing climate change impacts and deciding on a course of action. The framework can be applied from the systems planning level down to the scale of individual projects. The framework described in this chapter was tested in three states and modified based on feedback from state department of transportation (DOT) officials.

It is important to note at the outset that the research team could find no state transportation agency that has undertaken all of the steps of the diagnostic framework—or for that matter adaptation planning in general (at least in an organized and systematic way). Thus, the assessment of most of the steps of the diagnostic framework had to rely on state DOT officials' perspectives on the value and level of difficulty associated with undertaking each step. In addition, as will be found later in the guide, how adaptation strategies for reconstructing/rehabilitating existing infrastructure are approached might be different from the approach used for projects on new rights-of-way.

The approach described in the following section benefited from a review of climate adaptation guides developed in other countries (see, for example, Black et al. 2010; Bruce et al. 2006; Commonwealth of Australia 2006; CSIRO et al. 2007; Greater London Authority 2005; Nobe et al. 2005; Norwell 2004; Canadian Institute of Planners 2011; PIEVC and Engineers Canada 2008, 2009; Scotland Ministry of Transport 2011; Swedish Commission on Climate and Vulnerability 2007). Also, several agencies in the United States have developed approaches toward adaptation planning that serve as useful examples of how such planning can be done (see, for example, ICF International and Parsons Brinckerhoff 2011; Major and O'Grady 2010; WSDOT 2011; Metropolitan Transportation Commission et al. 2011; North Jersey Transportation Planning Authority 2011; Snover et al. 2007; SSFM International 2011; and Virginia Department of Transportation 2011).

What Are the Steps for Adaptation Planning?

Figure I.2 shows a diagnostic framework that focuses on identifying and managing assets and asset characteristics that are potentially vulnerable to negative (and inherently uncertain) impacts of climate change. The approach is based on the general concept of adaptive management, which has been formulated from the evolving philosophies and practices of environmental managers. Adaptive management is more than simply monitoring action outcomes and adjusting practices accordingly; it involves predicting future conditions and the outcomes of related management

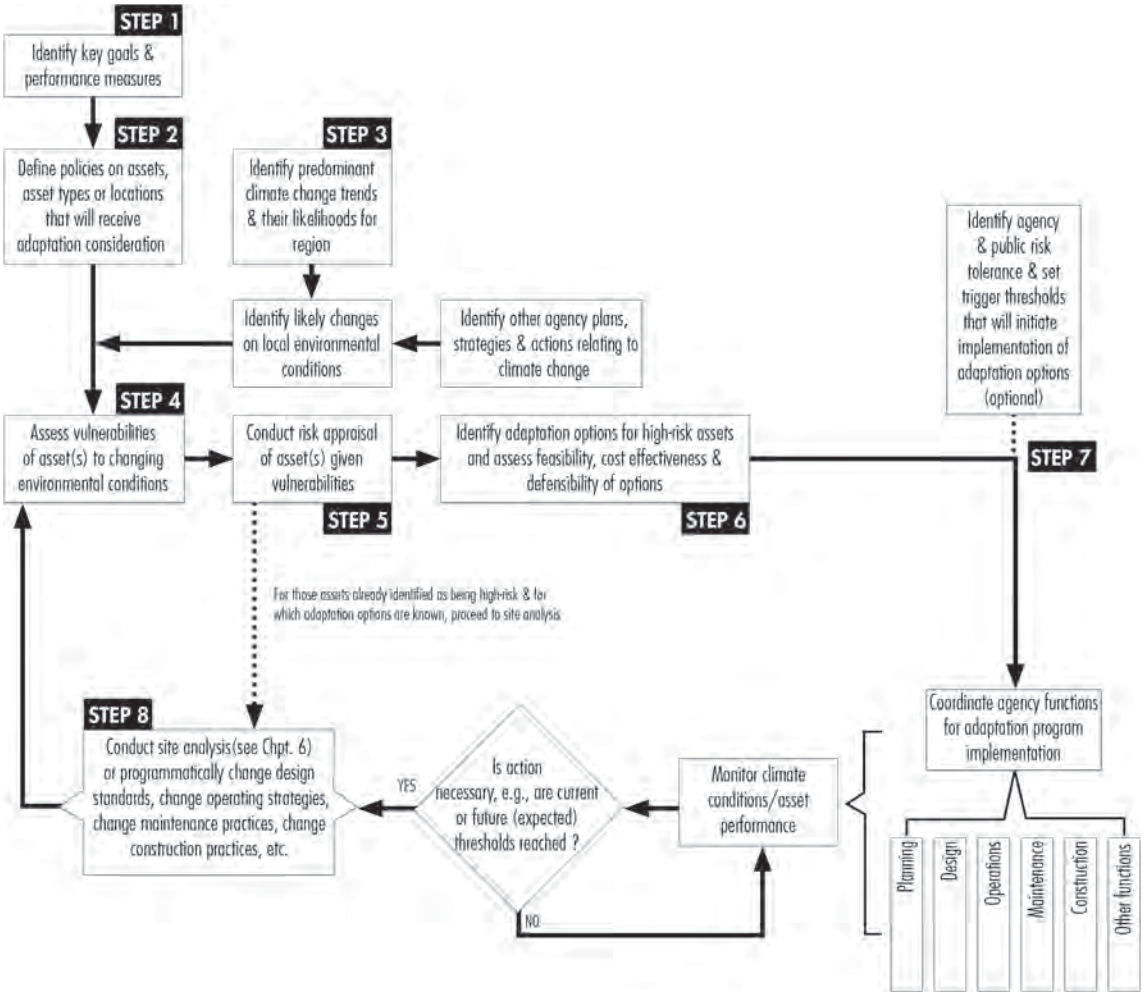


Figure I.2. Adaptation diagnostic framework.

policies as well as testing alternative management practices designed to address new and uncertain conditions.

An adaptive systems management approach to transportation infrastructure management provides a structured framework for characterizing future risks and developing new and evolving strategies to minimize *system* risk over time. Such a risk assessment approach is particularly vital for infrastructure systems and components that have long service lives (greater than 40 to 50 years). Infrastructure designed for a shorter service life has inherent adaptation opportunities incorporated into the relatively rapid facility replacement schedule that can account for significant changes in environmental conditions. Nonetheless, a process of identifying vulnerabilities and performance deterioration given changing environmental conditions should be considered for infrastructure with short service lives so that appropriate adjustments in design, construction, operation, and maintenance practices can be effectively implemented over time.

The diagnostic framework begins by establishing the overall focus and approach of an adaptation study. Thus, the goals for the analysis and what types of assets will receive attention should be established. For example, the focus might be on only those assets where experience with extreme weather suggests future problems will exist or on assets that are critical to network performance (e.g., a major bridge crossing), regardless of experience at that location. It is important to establish this study focus early in the process.

The framework then determines the likely future climatic and weather conditions. In other words, if the goal is to develop strategies to protect assets from higher-than-normal environmental stresses, there has to be some sense of what these stresses are likely to be. There are many ways of producing these estimates, each one having varying levels of uncertainty associated with the estimate. This guide discusses the assumptions, approaches, and outcomes of global circulation models and emissions scenarios, one of the most-used sources of such estimates.

Given the targeted assets and the type and level of climatic conditions to be faced, the vulnerability of these assets to the stresses that will be placed on them can now be determined. For example, are critical bridges designed to withstand much higher flood flows? Are culverts on key roads likely to handle some percentage increase in flows due to more intense storms? Is pavement likely to withstand more prolonged exposure to high-intensity heat? Through the vulnerability assessment process, transportation officials can determine which assets are likely to fail before others given expected environmental conditions.

Once the assets that are most vulnerable are known, the level of risk associated with the possibility of an asset failing must be determined. Risk analysis is a critical element of adaptation planning, and yet one that is most often misunderstood. In this case, risk encompasses all of the economic, social, and infrastructure costs associated with asset failure. Thus, for example, a bridge might not have as high a probability of failure given expected environmental stresses as others, but if the bridge fails, it will isolate a community for a long time with no alternative routes serving the community. In such a case, transportation officials might assign a very high risk value to that bridge. However, another bridge with a higher probability of failure, but lower consequences if failure does occur—for example, alternative travel routes may minimize the disruption to travelers and to the surrounding communities—might not receive as high a risk value.

The remaining steps in the diagnostic framework focus on identifying, assessing, and costing alternative strategies for protecting the high-risk assets. In some cases, this process requires a specific-site analysis where engineering strategies are analyzed; in other situations, this might mean establishing policies (e.g., construction work during high heat) to minimize impacts. This process also includes developing organizational capability to plan for climate adaptation and to respond to events when they occur.

The key steps in the diagnostic framework are discussed below in more detail.

Step 1: Identify Key Goals and Performance Measures

The adaptation diagnostic framework begins with identifying what is really important to the agency or jurisdiction concerning potential disruption to transportation system or facilities. At a high level, this includes goals and objectives. At a systems management level, this includes performance measures. Thus, for example, goals and performance measures could reflect economic impacts, disruptions of passenger and freight flows, harmful environmental impacts, etc. In the context of adaptation, an agency might be mostly concerned with protecting those assets that handle the most critical flows of passengers and goods through its jurisdiction, such as interstate highways, airports, or port terminals. Or, in the context of extreme weather events, it might focus on roads that serve as major evacuation routes and/or roads that will likely serve as routes serving recovery efforts. Or, focus might be given to routes and services that will provide access to emergency management and medical facilities. It is important that these measures be identified early in the process because they influence the type of information produced and data collected as part of the adaptation process. They feed directly into the next phase, defining policies that will focus agency attention on identified transportation assets.

Step 2: Define Policies on Assets, Asset Types, or Locations That Will Receive Adaptation Consideration

Changes in climate can affect many different components of a transportation system. Depending on the type of hazard or threat, the impact to the integrity and resiliency of the system will vary. Given limited resources and thus a constrained capacity to modify an entire network, some agencies might choose to establish policies that limit their analysis to only those assets that are critical to network performance or are important in achieving other objectives (e.g., protecting strategic economic resources such as major employment centers, industrial areas, etc.). Or because of historical experience with weather-related disruptions, the agency might choose to focus its attention on critical locations where weather-related disruptions are expected. These objectives follow directly from Step 1.

If an agency wants to conduct a systematic process for identifying the most critical assets, the criteria for identifying the assets, asset types, or important locations might include (1) high volume flows, (2) linkage to important centers such as military bases or intermodal terminals, (3) serving highly vulnerable populations, (4) functioning as emergency response or evacuation routes, (5) condition (e.g., older assets might be more vulnerable than newer ones), and (6) having an important role in the connectivity of the national or state transportation network.

It is important to note that such a systematic process could require a substantial effort on the part of the agency or jurisdiction. As is typical in any planning process undertaken in a public environment, the process of identifying critical assets will likely be done in an open and participatory way, with opportunities provided for many groups and individuals to propose their own criteria for what is critical to the community.

In addition, focusing only on higher level assets, many of which are already built to a higher design standard, runs the risk of missing serious issues facing non-critical (from a use or economic perspective) assets. For example, non-critical assets may be more vulnerable to climate changes due to lower design standards. If so, the costs to the agency of many failures on the larger non-critical network could be substantial. Having knowledge of this could be critical to effective adaptation planning. Also, if many non-critical assets fail, the diverted traffic can have implications on the performance of the critical assets. It is for reasons such as these that the agency should establish policies upfront that direct the adaptation analysis.

Step 3: Identify Climate Changes and Effects on Local Environmental Conditions

The climate will change everywhere, but the change will vary depending on the part of the world. For example, coastal cities will likely face very different changes in environmental conditions than inland cities, most notably sea-level rise and storm surges. Some places will see more total precipitation while others will see less. Step 3 identifies over the long term those changes in climate and the corresponding changes in local environmental conditions that could affect transportation design and operation. To identify climate changes and the effects on local environmental conditions, transportation officials will need to review updated regional and local climate modeling studies—or at the very least deduce local impacts from national and global climate studies. It is important to note that the current state of the practice of climate modeling varies by type of variable being forecast (e.g., increase in temperature is highly likely while there is a lot of uncertainty on regional changes in precipitation) and by change in the type of local weather condition (e.g., most models forecast more intense thunderstorms but there is very little consensus on whether there will be more tornados). Officials thus need to consider such information as being the best current science can produce.

The United States Geological Survey (USGS) and other government agencies are in various stages of producing downscaled climate data—that is, data at more disaggregate levels (such as an 8 mile by 8 mile grid cell)—that reflect changes in average climatic conditions as well as in extreme values (see Chapter 3). Thus, although currently many jurisdictions do not have such data, it will likely be more available in future years.

Washington State DOT (WSDOT), for example, used climate information assembled by the University of Washington Climate Impacts Group (CIG) for the 2009 Washington Climate Change Impacts Assessment. The assessment used future climate projections from global circulation models (GCM) in the 2007 Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report. These global climate change projections were regionally downscaled (both statistically and dynamically, see Chapter 3). The projections were based on scenarios of relatively moderate and low greenhouse gas (GHG) emissions during the century. The study concluded that the combination of increases in precipitation, increases in number of storms, less snow pack, and more runoff would generally result in more flooding and erosion.

With respect to sea-level rise (SLR), WSDOT officials were less certain as to an accepted forecast value. Accordingly, WSDOT generalized the CIG's SLR results into 2- and 4-foot scenarios, with potential for added storm surge. When SLR was coupled with increases in intense precipitation, runoff, and storm surge, it was determined that major impacts on infrastructure could occur, including inundation of low-lying areas, flooding, and erosion.

Step 4: Assess the Vulnerabilities of Asset(s) to Changing Environmental Conditions

Step 4 matches the results of the previous two steps and assesses how vulnerable targeted assets are likely to be to changes in local environmental and weather conditions. This assessment might entail, for example, examining potential flooding and the ability of drainage systems to handle greater flow demands or the likelihood of some segments of a facility being inundated with more frequent and severe storms. The vulnerability assessment might entail engineering analyses of the asset and the likelihood of different asset components failing due to environmental factors (see Chapter 6).

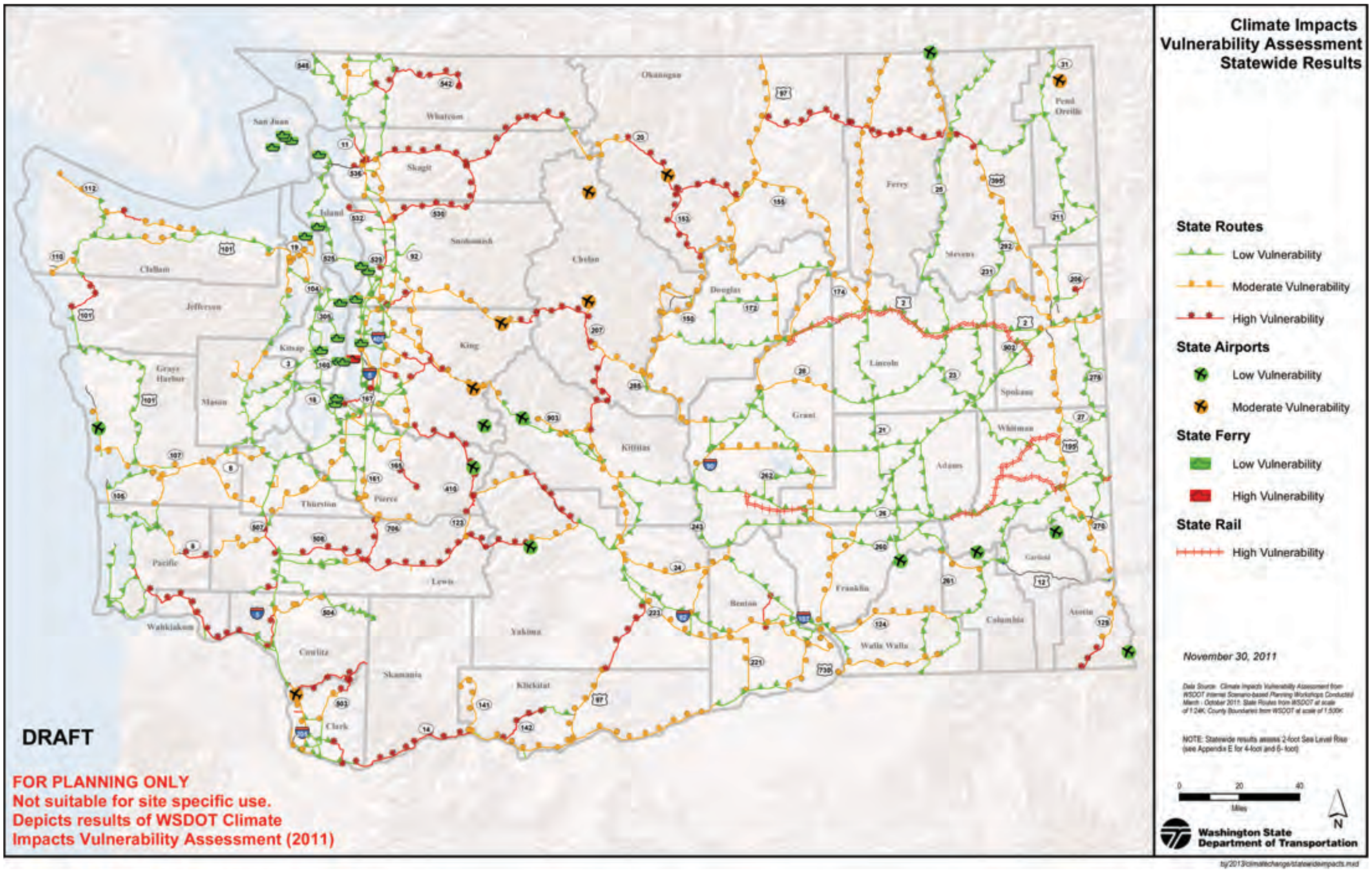
Expected Climate Change in Michigan

A tool called SimCLIM was used to project potential climate changes for Michigan. The study selected eight general circulation models based on their ability to simulate current precipitation patterns globally, in the United States, and in the upper Midwest. The study used the average values of the eight models and developed the following projections:

- Change in average precipitation from November through April, currently the months during which snow falls and can accumulate. Total precipitation over this period is an indicator of the size of the snowpack.
- Change in average March and April precipitation, the two months that are important for determining peak flow in the Kalamazoo River.
- Change in temperature for November through April and individually for March and April. The seasonal temperatures affect the total size of the snowpack. March and April temperatures determine when peak snowmelt will occur.

- Change in intense precipitation in April and annually. Change in April can be used to estimate change in potential for flooding during the spring snowmelt period. Annual change could be used to reflect change in the highest annual precipitation event. The study estimated change for two types of extreme events: the 24-hour event and the 3-day event. Two return periods were examined: 25 years and 100 years. This provides an estimate of change for more common (1:25 year) and more extreme (1:100) year events.

The State of California, for example, has performed an assessment of its vulnerability to coastal flooding, including vulnerability of its transportation infrastructure. The vulnerability assessment utilized flood mapping studies from the Scripps Institution of Oceanography and probability calculations of 100-year flood events. The study identified the miles of roadways affected by estimated flood events but did not quantify the costs associated with flood damage. A logical next step for this or any vulnerability assessment is to fully quantify the risk to infrastructure so that engineering decisions are adequately informed. Figure I.3 shows the results of a transportation vulnerability assessment for Washington State.



Source: WSDOT (2012).

Figure I.3. Climate change–related vulnerability in Washington State.

In the diagnostic framework (Figure I.2), there is the possibility of proceeding directly to the identification of design or other solutions (Step 8) right after the vulnerability assessment and the risk appraisal (Steps 4 and 5). This relates back to Step 2 where policies on what asset, asset types, or locations will receive attention were established. However, the agency should proceed with caution in jumping right into adaptation actions so as to avoid applying them when in fact they are not needed. Thus, even in the case where certain types of assets have been targeted for adaptation efforts, the agency should still check to make sure a particular asset deserves such an effort.

Step 5: Conduct Risk Appraisal of Asset(s) Given Vulnerabilities

Risk appraisal, at a minimum, considers the likelihood of the climate change occurring and causing asset failure along with some characterization of the consequences of that failure (in terms of system performance, damage costs, safety risks, etc.). England's Highways Agency and Parsons Brinckerhoff (2008), for example, developed a risk appraisal process based on the following four elements:

- "*Uncertainty*—compound measure of current uncertainty in climate change predictions and the effects of climate change on the asset/activity."
- "*Rate of climate change*—measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity."
- "*Extent of disruption*—measure taking account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important if it affects a high proportion of the network, or a small number of highly strategic points on the network."
- "*Severity of disruption*—measure of the recovery time in case of a climate-related event (e.g., flood or landslip). This is separate from 'how bad' the actual event is when it occurs, e.g., how many running lanes [are lost]; it focuses on how easy/difficult it is to recover from the event, i.e., how long it takes to get those running lanes back into use."

The uncertainty and rate of climate change considerations provide a qualitative characterization of likelihood whereas the extent and severity of disruption elements characterize consequence. Chapter 5 provides more information on different approaches to risk appraisal.

Step 6: Identify Adaptation Options for High-Risk Assets and Assess Feasibility, Cost Effectiveness, and Defensibility of Options

Identifying and assessing appropriate strategies for the challenges facing critical infrastructure assets is a core component of the process shown in Figure I.2. Such strategies might include modifying operations and maintenance practices (such as developing and signing detour routes around areas at a heightened risk of road closure), designing extra redundancy into a project, providing above-normal reserve capacity, incorporating a greater sensitivity to the protection of critical elements of the project design (such as better protection against bridge scour or high winds), designing with different design standards that reflect changing conditions (such as higher bridge clearances for storm surges), or planning for more frequent disruptions. In particular with respect to design standards, a more robust approach could be adopted that takes into account risk and uncertainty.

In many ways, considering climate-induced changes in the design process follows a model that has been applied in earthquake engineering. Building codes and design standards have been changed to reflect the forces that will be applied to a structure during a seismic event. Substantial research on the response of materials, soils, and structures themselves has led to a better understanding of the factors that can be incorporated into engineering design to account for such extreme events. Similarly, other design contexts reflect forces that might be applied during collisions, fires, or heavy snows. The logical approach for considering the best design for climate-induced changes is to examine the relationship among the many different design contexts that a structure might be facing and determine which one "controls" the ultimate design.

Step 7: Coordinate Agency Functions for Adaptation Program Implementation (and optionally identify agency/public risk tolerance and set trigger thresholds)

This step in the diagnostic framework identifies which agency functions will be affected the most by changes in infrastructure management practices. Given the range of climate stressors (characteristics of the climate that could in some way affect the design, construction, maintenance, and operations of a transportation system or facility) and extreme weather events that states might face, it is likely that many of an agency's functional units—planning, project development, operations, maintenance, etc.—will have some role to play in developing a strategy. Maryland, for example, identified 16 agency units within the State Highway Administration that had a role to play in implementing its climate adaptation policy. Furthermore, it is reasonable to expect that the new challenges imposed upon transportation infrastructure managers by climate change will require new adaptive efforts that are dependent upon interagency cooperation. For example, an analysis of the impact of riverine flooding on transportation and other infrastructures may determine that the most cost-effective adaptation will involve a combination of bridge design adjustments and river channel widening, thus necessitating coordination between the transportation agency and the U.S. Army Corps of Engineers (USACE). Planning for failures (e.g., prepositioning replacement materials for highly vulnerable locations) is important too and may be needed more with increasing frequency and intensity of extreme weather events.

Many of the changes in climate considered as part of this assessment will likely not occur for decades, and it is also likely that the full extent of the estimated impacts of such changes on transportation facilities or systems may not occur until even further into the future. An agency might want to establish "trigger" thresholds that serve as an early warning system so that agency officials can examine alternative ways of designing, constructing, operating, and maintaining transportation infrastructure in response to higher likelihoods of changed environmental conditions. For example, precipitation levels might not change significantly enough over the expected life of drainage structures to change culvert designs today, but at some point in the future higher levels of precipitation would trigger a review of existing culvert design or of the assumptions that go into such design because the new precipitation levels would have become the norm.

The adaptive systems management approach is foremost an iterative process. Realization of the intended benefits of this approach (minimization of risk and development of cost-effective adaptation strategies) requires that the latest information on changing environmental conditions and system performance priorities be incorporated into the process through monitoring external conditions and asset performance/condition, either in an asset management system or through some other means.

Step 8: Conduct Site Analysis or Modify Design Standards, Operating Strategies, Maintenance Strategies, Construction Practices, etc.

Once a decision is made to take action, the agency should implement whatever cost-effective strategies seem most appropriate. As shown in Figure I.2, this could range from changes in design procedures to changes in construction practices. If the focus of the adaptation assessment is on specific assets in a particular location, more detailed engineering site analyses might be needed.

The adaptation strategies under study by King County, Washington's Road Services Division provide an illustrative example of the range of adaptation strategies an individual transportation agency might consider (King County Road Services 2012):

- Replacing or rehabilitating bridges in order to improve floodwaters conveyance and to avoid scour during high flows
- Using pervious pavement and other low-impact development methodologies to manage stormwater through reduced runoff and on-site flow control
- Modifying existing seawalls to avoid failures in transportation facilities
- Evaluating roadways to minimize their vulnerability to potential risk from landslides, erosion, or other failure triggers
- Developing new strategies to effectively respond to increasingly intense storms, including providing alternative transportation access
- Managing construction and operations to minimize effects of seasonal weather extremes
- Identifying opportunities to incorporate habitat improvements that buffer the effects of climate change on ecosystem health into project designs.

More detail on potential actions that can be taken in response to identified threats is found in Chapter 4.

Once such actions are implemented, the adaptation assessment process links back to assessing vulnerabilities. Given that the agency has now changed the status or condition of a particular asset, at some point in the future it might be necessary to determine yet again what future vulnerabilities might occur given this new condition.

What Is the Relationship between Climate Change and Transportation Planning?

The diagnostic framework shown in Figure I.2 is designed to be a stand-alone process for undertaking an adaptation assessment. In most cases, transportation agencies will (and should) link adaptation planning efforts to existing agency processes and procedures. One of these linkages will most likely be with the transportation planning process (Schmidt and Meyer 2009; FHWA 2011). This section describes how adaptation considerations can be incorporated into a typical transportation planning process.

The first step of a transportation planning study is to prepare a *work scope.* The scope describes the range of issues that will be covered as well as the steps that will be undertaken. With respect to adaptation, the scope can describe to what extent climate adaptation will be addressed as part of the plan. It should explain why it might be necessary to look beyond the traditional 20- to 25-year time horizon for a typical planning effort so as to analyze the potential impacts of climate change to the highway system. The scope should include a discussion of how climate stressors will be forecast for the particular state or region and at what level of detail.

The *vision, goals, and objectives* for a transportation planning study usually include more than just transportation topics, encompassing such issues as environmental quality, economic competitiveness, community quality of life, public health, etc. Goals and objectives further define how the vision will be accomplished. Goals and objectives also lead to the development of performance measures that can be used to monitor the performance of the highway system. This step is where planning organizations can decide how important it is to address climate change adaptation as part of the planning effort. If anticipating potential climate change is part of the state or community vision, the more likely it is that planning will include goals and objectives that address climate change, and thus lead to analysis and assessment later in the process.

Performance measures can be used to identify where the system is vulnerable to climate change, i.e., where climate change risks impede the meeting of system or agency goals. Performance measures relating to program implementation could be used to assess how well climate change impacts and strategies are addressed over the planning horizon. For instance, performance measures could evaluate how well the agency implements climate change adaptation measures such as strengthening threatened infrastructure or relocating threatened infrastructure. Also some measures relating to the changing weather and environmental conditions (e.g., higher frequency and more intense storms that result in higher than average flooding of roadways) could provide an early warning system for changes in climate that should be considered when planning future infrastructure.

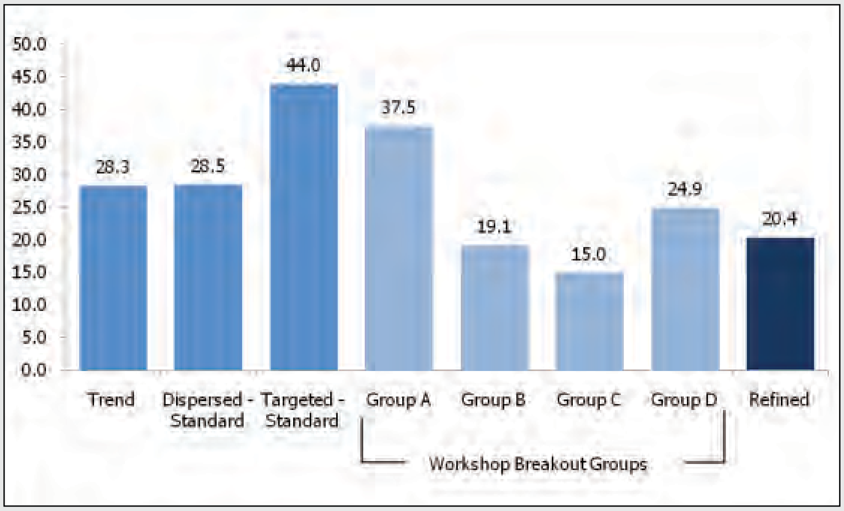
Data and data analysis are used to identify existing and future transportation deficiencies usually relating to congestion, safety, connectivity, and system performance, while also analyzing other potential issues such as economic development, land use, social, and environmental concerns that may affect or be affected by the transportation system. If climate change and highway adaptation are to be considered as part of the planning effort, this step will also include the level at which they will be considered, the approach toward climate change projections, and how highway vulnerability will be determined (Brand et al. 2000).

If scenario analysis will be used as part of the planning effort, this step includes the definition of different scenarios that take into account alternative futures that help define the context within which the transportation system will perform. As part of scenario development, planners could consider different climate futures depending on the degree of urgency that climate change has with key constituencies and decision makers. The diagnostic framework could be applied to the adaptation strategies in all the scenarios or the ones that decision makers decide are the most likely to occur. This step would consider the cost effectiveness of the likely adaptation strategies for each scenario factoring in the risk of climate change, vulnerability of the highway system, and the benefits and costs of the adaptation strategies.

One of the key inputs into transportation planning (and eventually programming) is determining how much revenue will be available in the future and the sources of these funds. This step would include developing *financial assumptions* during the life span of the plan. Metropolitan planning organizations (MPOs) are required to produce fiscally constrained plans and programs while state DOTs must develop fiscally constrained programs but not fiscally constrained long-range plans. This step is important for a state's or region's adaptation program because it will outline how adaptation strategies will likely be funded. They could be part of more traditional programs, such as bridge replacement or rehabilitation where some amount of additional funding is provided to make adaptation-related improvements, or some funds might be set aside to "fix" those parts of the road network that will receive increasing levels of stress over time, e.g., road sections that already tend to flood during high-intensity storms.

Scenario Analysis to Determine Vulnerable Populations to Sea-Level Rise on Cape Cod

Three federal agencies—the Federal Highway Administration, National Park Service and the U.S. Fish and Wildlife Service—sponsored a scenario-planning effort on Cape Cod, one of the nation's most ecologically sensitive areas. Lying off the coast of Massachusetts, Cape Cod is also expected to be one of the first areas in the United States to be affected by SLR. To determine the level of impact of SLR to the future population on the Cape, local officials and residents participated in scenario planning that examined different assumptions on future population growth and where the new population would reside. The effort included both a technical analysis by consultants assuming varying rates of growth and locations of residence, and then a workshop-generated set of scenarios that were based on resident input. A "refined" scenario was then used to determine what percentage of the population might be affected by SLR. The figure below shows the results.



Percentage of population vulnerable to sea level rise given different scenarios

According to the final report, "scenario planning provided participants an opportunity to experiment, to explore how different information overlapped, and to discuss tradeoffs. One of the key benefits of scenario-planning software is its ability to provide fairly immediate feedback on development and transportation decisions and to provide a tool by which to explore and test the implications of different decisions."

Source: FHWA et al. (2011).

Institutional, Financial, and Political Obstacles

The diagnostic framework in Figure I.2 mirrors the thought process that transportation agencies are using around the world in adaptation planning. However, this framework focuses on the technical aspects of adaptation planning, whereas many of the state officials participating in the testing of this framework noted practical institutional, financial, and political issues. They noted that, while there are several reports on how to do adaptation planning technically, there is a dearth of guidance and materials for helping DOTs to implement adaptations in the context of shrinking budgets and public skepticism. One response has been to undertake "no regrets" adaptation efforts, which in essence are actions that can be easily implemented and/or have other benefits. The financial and political issues are magnified all the more when adaptation greatly adds to the initial project costs and requires additional lands to be taken from private property owners for right-of-way, thus, the reason the step in the diagnostic framework was called "assess feasibility, cost effectiveness and *defensibility* of adaptation strategies." This step might involve a discussion of the political and institutional factors and strategies that inevitably shape adaptation decision making.

A number of potential strategies for addressing these institutional barriers to adaptation might include (1) emphasizing the possible network impacts from severe weather events that may become more common under climate change, (2) using network disruptions caused by severe weather events to incorporate adaptive design in at least the affected roadway segment (potential obstacles to such a strategy might be federal rules that encourage replacement in kind), and (3) publishing adaptation guidelines that provide professional best practice justification for the consideration of adaptation strategies.

Another important aspect of the diagnostic framework is its relationship with other elements of an agency's typical project development process. For example, the project design that comes out of an agency's engineering design unit is often subject to value engineering. Some of the state DOT officials participating in the review of the diagnostic framework felt that design adaptations associated with a project would be a prime target for cuts during a value-engineering exercise because of the potential extra costs associated with adaptive designs. The diagnostic framework in Figure I.2, therefore, must be integrated into the agency's standard engineering, operating, and maintenance approaches, and steps taken to make sure that one part of an agency's standard operating procedures does not negate actions taken to make a project less vulnerable to future environmental stresses.

How Does the Framework Fit into the Organization of the Guide?

The remaining chapters of this guide provide directions and examples of how the diagnostic framework in Figure I.2 can be used to promote a more adaptive process for transportation agency actions with respect to future environmental conditions. Figure I.4 shows how the diagnostic framework leads to the organization of this guide.

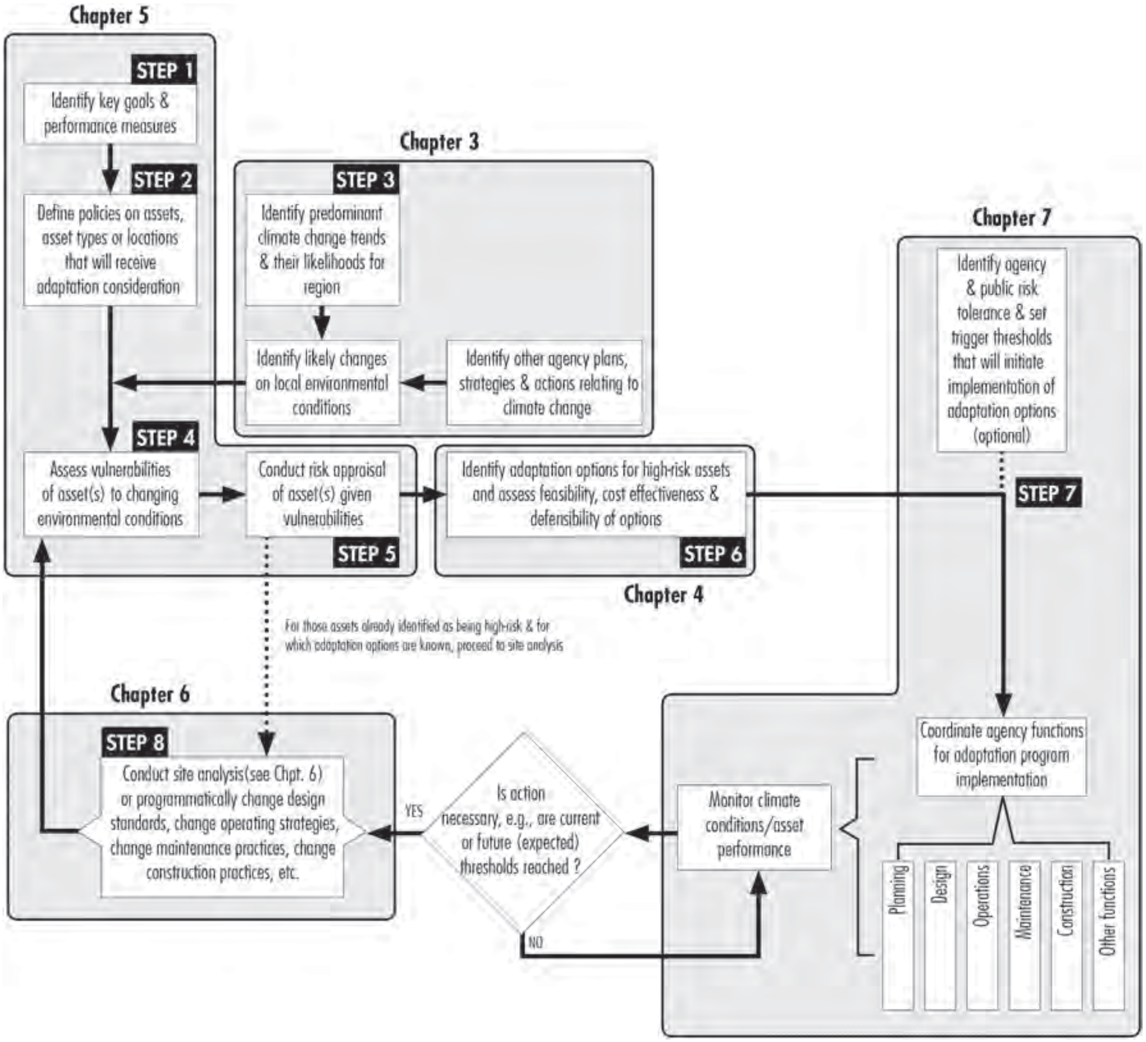


Figure I.4. Guide organization based on diagnostic framework.

CHAPTER 3

Projected Changes in the Climate

Determining the types and potential magnitudes of changes in climate that could affect transportation systems is one of the most important early steps in the diagnostic framework. Such information can be used in efforts to increase the robustness and resilience of transportation systems to changes that might represent threats to infrastructure and system operations. **A key concept to keep in mind when planning for climate change is that the climate is *known* to be already changing and *will continue* to change, but *exactly how* it will change*, particularly at the local scale* is not known.** This uncertainty poses a real challenge for transportation decision makers and for others responsible for infrastructure systems potentially affected by climate change. Making investment and/or operations decisions in anticipation of changes in climate fundamentally means considering the uncertainties associated with the expected changes.

Climate stressors are characteristics of the climate, such as average temperature, temperature ranges, average and seasonal precipitation, and extreme weather events, that could in some way affect the design, construction, maintenance, and operations of a transportation system or facility. Preliminary experience with adaptation planning from around the world indicates that this initial step varies in sophistication from the use of expert panels to large-scale climate modeling. The approach used in any particular adaptation effort will most likely relate to the available budget, the availability of climate change projections from other sources (e.g., a state university), and the overall goal of the study. For example, in the latter case, if the goal is to identify sections of roadway that are vulnerable to flooding, maintenance records could be examined to see where such flooding has occurred in the past or sessions with the agency's operations and maintenance staff could be conducted to get their input on where problems potentially exist (if the agency is looking at a broad area, doing this might require substantial resources). The downside of this approach is that areas that were not flood-prone in the past may be flood-prone with future climate changes. Finding these areas requires some form of climate forecast to be used as input into the adaptation study, most often coming from an organization other than the transportation agency. It is important therefore that transportation officials understand the basics of climate modeling so they are aware of the information that can be provided by such tools as well as their limitations. The following sections describe what is known and not known about climate modeling and how information from climate models can be used to inform decision making.

What Do Climate Models Do?

The main tools used to simulate global climate and the effects of increased levels of greenhouse gases are called "general circulation models," more precisely, atmosphere-ocean general circulation models. As their name implies, these models capture changes in the atmosphere and oceans and their interactions. There are simpler models that can simulate changes in climate at the global average level. An example is the MAGICC model (Wigley 2008, 2009), used for this research, which can estimate changes in GHG concentrations, average global temperatures, and sea levels.

Multiple models are usually used, all guided by IPCC-specified parameters. These models simulate the atmospheric, oceanic, and land processes and interrelationships that affect climate. They typically divide the world into grid boxes that can be hundreds of miles across. At each simulated point in time in each grid box are estimated levels of temperature, precipitation, and other climate variables. In reality, a uniform level of weather conditions is not likely to be found across the several hundred miles in each grid box; thus, it is important to know that GCMs do not estimate spatial variability of climate characteristics within the model grid boxes.

Because GCMs only simulate climate at relatively low spatial resolution, and because higher spatial resolution is often desired, a method called "downscaling" is commonly used. Downscaling starts with the output from GCMs and then estimates climate conditions at higher spatial resolution. One approach, called statistical downscaling, uses observed-data statistics on the relationship between climate at a large scale (low resolution) and local scale (high resolution) to estimate how climate will change at a specific location. This approach assumes that the statistical relationship between the large-scale climate simulated by GCMs, such as pressure patterns, and climate at the local scale (in the case of statistical modeling, it can be a specific location) does not change from the present relationship. Assuming the relationship is unchanged, the present-day relationship can be determined and used to estimate how future climate at a specific location will change. This standard procedure involves additional uncertainties because it is unknown if the relationship between large-scale climate and climate at a specific location will indeed remain unchanged.

A second approach to downscaling is to use higher resolution climate models that cover only specific regions of the globe rather than the whole planet. These regional climate models (RCMs) divide a region such as North America into much smaller grid boxes than those found in GCMs. These grid boxes may be as small as a few tens of miles across. They can capture features such as mountains and large water bodies that a typical GCM cannot resolve. Regional models, however, must use inputs from the global models (as is the case for statistical downscaling). If two GCMs yield different large-scale patterns of climate, then the regional models will give different results depending on which GCM is used. In addition, RCMs do not accurately simulate all relevant climate processes. **Fundamentally, while downscaling can provide more *precision* in representing future climate conditions at a regional and local scale, in its current form, in general, it does not provide more *accuracy.***

What Are Emission Scenarios?

GHG emissions from human activities such as the burning of fossil fuels (e.g., coal, oil, natural gas), deforestation, and various agricultural practices have been increasing since the beginning of the Industrial Revolution. The concentration of these gases is increasing and so is the temperature of the lower atmosphere (Solomon et al. 2007). In the absence of technologies or policies to reduce such emissions, emission levels will in all likelihood continue increasing for many decades to come. Exactly how much they, along with other factors (such as aerosols) that also affect global climate, may increase is uncertain and estimates vary widely.

Intergovernmental Panel on Climate Change 2009

The IPCC developed a set of socioeconomic scenarios in 2000 for world population growth, industrial and agricultural development, and energy use from which it calculated expected global GHG emissions. *Emissions Scenarios* [also known as the Special Report on Emissions

Scenarios (SRES); Nakicenovic et al. 2000] includes projections based on assumptions ranging from very high economic growth and reliance on fossil fuels to scenarios with a high emphasis on environmental concerns and limited population growth (see Table I.2).

Carbon dioxide (CO_2) is the most important human-emitted GHG in terms of its total effect on climate. Carbon dioxide, like many GHGs, occurs naturally and its concentration in the atmosphere was about 280 parts per million (ppm) before the Industrial Revolution. It is currently over 390 ppm (Earth System Research Laboratory 2012). Water vapor is the atmospheric constituent with the largest effect on temperature. Human activity is not emitting more water vapor into the atmosphere, but rising temperatures allow the atmosphere to hold more water vapor, which further enhances warming. As can be seen in Table I.2, the projected concentrations of CO_2 across five SRES scenarios differ only slightly by 2050. The B1 and B2 scenarios hold CO_2 levels just below 500 ppm, while the other scenarios result in CO_2 levels above 500 ppm. With the exceptions of the A1FI scenario and the optimistic B1 scenario, the global mean temperature (GMT) projections for the other emissions scenarios—A2, A1B, and B2—hardly differ by 2050.

By 2100, the five emissions scenarios diverge considerably and the concentrations of CO_2 in each scenario differ even more. The CO_2 concentration estimate in the B1 scenario is over 500 ppm. In contrast, the B2 scenario is over 600 ppm; the A1B scenario increases concentrations to over 700 ppm; the A2 scenario puts CO_2 over 800 ppm; and the highest of the SRES scenarios, the A1FI scenario, results in CO_2 levels close to 1,000 ppm. So, by 2100, the difference in CO_2 concentrations across this set of emissions scenarios is almost a factor of two.

The relationship is not linear, but more GHGs in the atmosphere will result in more warming. The relatively low-emissions B1 scenario results in a GMT increase of 1.5°C (2.7°F) over 2010

Table I.2. Carbon dioxide levels and temperature change from the Special Report on Emissions Scenarios.

SRES Scenario	Key Assumptions	CO_2 Concentration 2050 (ppm)	Increase in GMT 2010 to 2050 (°C/°F)	CO_2 Concentration 2100 (ppm)	Increase in GMT 2010 to 2100 (°C/°F)
A1FI	Very high rates of growth in global income, moderate population growth, and very high fossil fuel use	570	1.5 (2.7)	993	4.1 (7.4)
A2	Moderate rates of economic growth, but very high rates of population growth	533	1.1 (2.0)	867	3.4 (6.1)
A1B	Same economic and population assumptions as the A1FI scenario, but assumes more use of low-carbon-emitting power sources and clean technologies	533	1.2 (2.2)	717	2.6 (4.7)
B2	Population growth lower than A2; intermediate economic growth and more diverse technological change	476	1.1 (1.9)	620	2.2 (4.0)
B1	Same population growth as A1FI and A1B, but assumes a more service-oriented economy and much more use of low-carbon-emitting power sources and clean technologies	487	0.8 (1.5)	538	1.5 (2.7)

GMT = global mean temperature.
Source: Nakićenovic et al. (2000).

values, while the higher A1FI scenario results in a 4.1°C (7.4°F) increase, a factor of 2.7. It is not just differences in GHG emissions, but also differences in emissions of aerosols that lead to the different levels of warming. Even where there are similar CO_2 levels across different SRES scenarios, in some cases, there are differences in realized change in GMT. These differences are most likely due to differences between the scenarios in the emissions of non-CO_2 GHGs and aerosols.

CO_2 is not the only greenhouse gas. The scenarios generally consider emissions of a range of non-CO_2 GHGs, such as methane, nitrous oxide, halocarbons, etc. To combine the effects of these various gases, it is common practice to use "radiative forcing" as a way of aggregating their effects—radiative forcing is a measure of how much energy is trapped in the atmosphere by the increases in GHGs, summed over all GHGs.

Intergovernmental Panel on Climate Change 2014

As part of its Fifth Assessment Report due to be published in 2014, the IPCC is now using a new set of four scenarios called "representative concentration pathways" (RCPs; Moss et al. 2010). The RCPs assume different stabilization levels or targets for radiative forcing, and they span a wide range of possibilities. The RCPs evolved through the selection of socioeconomically based scenarios (from the large set that is available in the literature) to match a chosen set of targets. A key point is that there are many possible socioeconomic pathways and policy choices that can lead to the same (or at least very similar) levels of radiative forcing. The IPCC is currently developing multiple emissions scenarios for each RCP.

Table I.3 compares the RCPs with the SRES scenarios. The relative warming potential for each scenario is expressed as "CO_2 equivalent," which, like radiative forcing, combines the relative effect of different GHGs. It measures the effect relative to CO_2 (using the relative effect over 100 years). Note that for the same emissions scenario, the CO_2 equivalent value in Table I.3 is higher than the CO_2 concentration in Table I.2 because CO_2 equivalent accounts for the radiative forcing of all the GHGs, not just CO_2. The RCP 8.5 has a CO_2 equivalence value by 2100 between the A1FI and A2 SRES scenarios; RCP 6 is very close to B2; RCP 4.5 is close to the B1 scenario; and RCP 2.6 has no equivalent in the SRES scenarios.

What Is Climate Sensitivity?

Climate sensitivity is defined as the eventual (equilibrium) warming that would occur if the amount of CO_2 in the atmosphere were doubled. This gives an indication of how much the climate will change, where "average global temperature" is the unit of measurement. CO_2 levels are usually compared between those before the Industrial Revolution (280 ppm) and a doubling

Table I.3. Radiative forcing in representative concentration pathways and SRES Scenarios, Year 2100.

RCP	CO_2 Equivalent (ppm)
8.5	1,396
6	779
4.5	586
2.6	453

SRES	CO_2 Equivalent (ppm)
A1FI	1,497
A2	1,265
A1B	875
B2	792
B1	595
–	–

(560 ppm), resulting in an estimate of how much average global temperatures will increase. Note that in the real climate system, actual warming lags considerably behind the potential equilibrium warming, because of the role of oceans (which can temporarily absorb heat)—just as a car does not immediately jump to top speed when the accelerator is floored. If the radiative forcing on the climate system were suddenly halted and kept constant, it would take the system many decades to reach equilibrium.

Climate sensitivity is estimated by running climate models with historical GHG changes and then comparing the results with observed changes. Note that models cannot be used alone to estimate climate sensitivity. The sensitivity in the model is strongly dependent on the internal physics of the model, and the way components of the climate system like clouds are simulated, so different models have a wide range of sensitivities. Scientists also examine information on how much warmer the Earth was tens of thousands or millions of years ago when CO_2 and other GHGs had higher (or lower) concentrations than present. So-called "paleo-climate" estimates rely on proxies to estimate how much warmer (or cooler) the climate was in the past and thus are more uncertain about temperature levels than are thermometer and satellite-based measurements of the current climate. The judgment of scientific experts is used to assess this information.

In 2007, the IPCC considered the projections from models, paleo-climate information, and expert judgment and stated that the best estimate of how much the average temperature of the Earth's atmosphere would increase with a CO_2 doubling is 3°C (about 5.4°F). Because climate models yield different results and historical and paleo-climate analyses yield different estimates of temperature associated with CO_2 doubling, scientists have defined a range of climate sensitivities. The IPCC said that there is a two-thirds chance that the true sensitivity is between 2°C (3.6°F) and 4.5°C (8.1°F). If there is a two-thirds chance that climate sensitivity is between 2°C and 4.5°C, then there is a one-third chance it is outside this range. The IPCC concluded that there is only approximately a one in 20 chance that climate sensitivity is below 1.5°C (2.7°F). Wigley et al. (2009) found that there is only a one in 20 chance that climate sensitivity is greater than 6°C (10.8°F). Thus, scientists have concluded that there is a nine in 10 chance that the true sensitivity is between 1.5°C and 6.0°C. This range represents a factor of 4.

Can Regional Climate Be Modeled?

Warming will happen across the planet and, on average, precipitation will increase. But, not all areas will get wetter; indeed, some will get drier. This is the result of changes such as shifts in the jet stream, which exerts control over where precipitation falls. GCMs' estimates of long-term *average* changes tend to be given much more credence than GCMs' simulation of climate variability. Multiple runs from a single GCM are averaged into an "ensemble" or the results of multiple GCMs are averaged together partly to even out the "noise" of natural variability from the models' simulation. In addition, research organizations such as the IPCC examine results from dozens of climate models to see if they consistently project the same changes in patterns of precipitation. This helps to better see the decadal or long-term changes in climate arising from human influences.

The reason it is difficult to forecast climate (like a weekly weather forecast) at a regional or local scale is natural variability, which includes factors such as El Niño and many other processes that operate on daily, monthly, annual, and decadal timescales. GCMs simulate these components of natural variability, but not accurately.

The El Niño Southern Oscillation (ENSO) is a critical part of this uncertainty, but not the only one. In what are called "El Niño years" (when temperatures at the surface of the tropical Pacific Ocean are above normal), winter storms tend to hit the California coast, leaving the

Pacific Northwest dry. During so-called "La Niña years" (when those sea surface temperatures in the tropical Pacific are cooler than normal), the storms are driven north, making the Pacific Northwest wet, but leaving California and many parts of the southern United States dry. ENSO fluctuations have consequences for climate around the world. If climate change were to change the frequencies of El Niño or La Niña events, it could have important consequences for rainfall in the western United States. So, can GCMs tell us what might happen to the frequencies of Los Niños and Las Niñas? The answer at present is "no." Part of the reason is that many climate models do not simulate current ENSO circulation patterns well nor do they agree on how ENSO will change.

In addition to ENSO, there are other important drivers of regional climate such as the Pacific Decadal Oscillation, the Madden–Julian Oscillation, and the North Atlantic Oscillation. These can influence climate on monthly to decadal timescales. How climate change will affect these drivers of climate variability is uncertain.

Natural variability will always be imposed on these low-frequency changes, and this will always have an important influence on climate variations such as whether particular years are wet or dry. The following discussion focuses on the long-term average (human-induced) component of future climate from emissions to both global and regional climate.

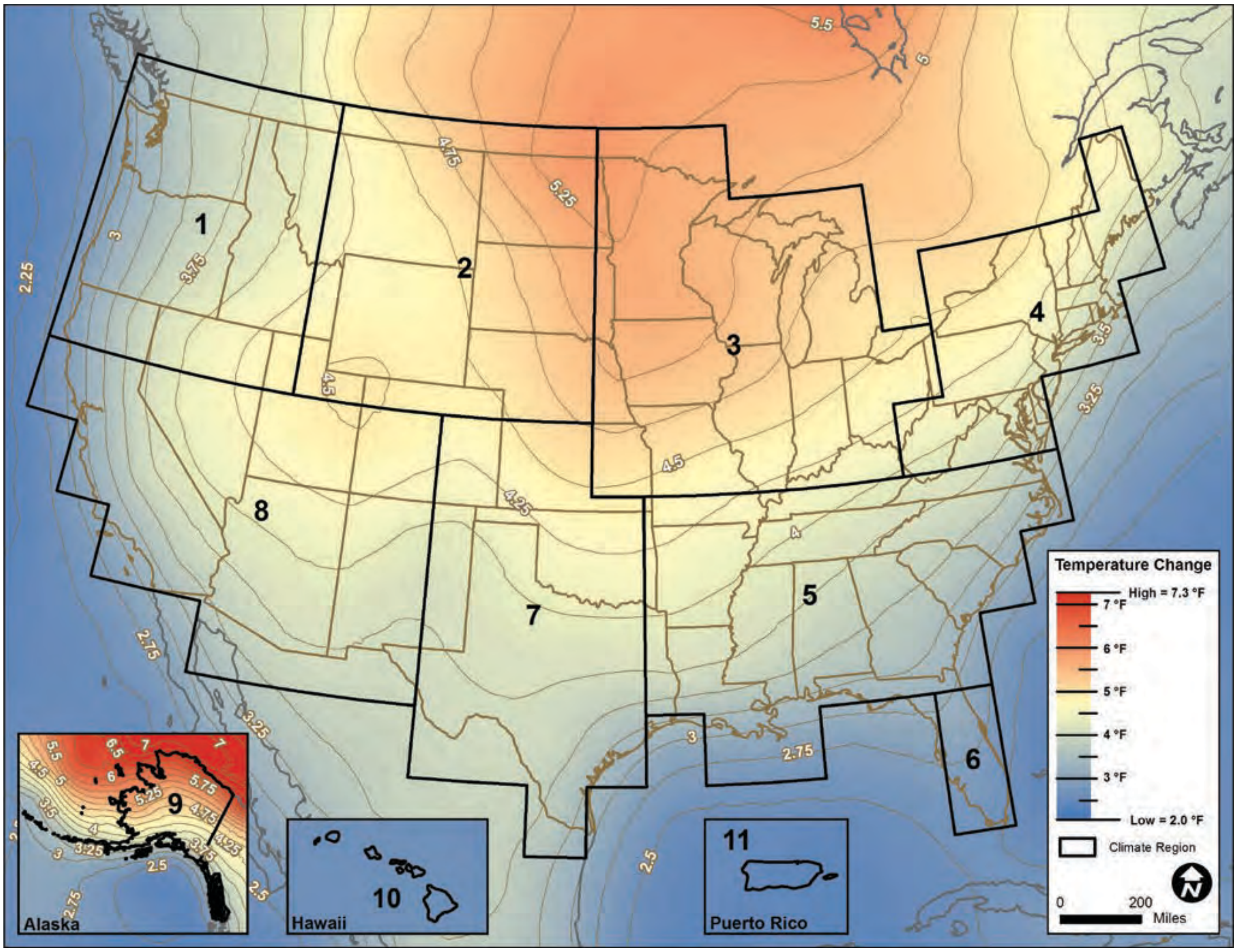
What Will the Climate Be Like in 2050?

Changes in climate were estimated in this research from 2010 to 2050, assuming a climate sensitivity of 3.0°C, and using the A1FI emissions scenario. As noted previously, the A1FI scenario is the highest of the SRES emissions scenarios that are widely used. Even though the SRES was published more than 10 years ago, it is difficult to say if one of the emissions scenarios is more likely than others. CO_2 emissions have run above and below the levels projected by the SRES scenarios for the last decade. For a few years they were running at or above the highest SRES scenarios (Raupach et al. 2007). They then dipped with the global recession. In recent years, emissions have been growing again (IEA 2011). This behavior suggests that actual emissions over coming decades *could* exceed what the IPCC projected. Yet, extrapolating from the last decade to the rest of the century is not a reliable method for projecting future GHG emissions. Nonetheless, the lack of a comprehensive global agreement to limit future GHG emissions together with the recent record of growing emissions suggest that actual emissions could be quite high for some time to come. Therefore, it is not unreasonable to use the A1FI emissions scenario in this analysis. But, as just noted, actual emissions could be lower or higher; therefore, change in climate could be less or more than reported in the following paragraphs. However, as will be discussed, the projections for 2050 from the A1FI, A2, and A1B emissions scenarios do not differ substantially.

Temperature

Figure I.5 presents average change in temperature in the United States from 2010 to 2050. Temperatures in the lower 48 states are projected to increase about 2.3°C (4.1°F) by 2050 relative to 2010. This average increase in regional temperatures is higher than the 1.5°C (2.7°F) global average temperature increase (see Table I.2). The United States, on average, is projected to warm by more than average global temperatures, partly because temperature changes over land are generally higher than those over oceans. Even though what is displayed in the figure is an average of 10 models, all of the GCMs project higher temperatures across the United States.

Note that in the last 50 years, average U.S. temperatures, including Alaska, increased by around 1.2°C (2°F), which means that temperatures in the lower 48 states increased by less than 2°F (Karl et al. 2009). The projected temperature change would result in an approximate doubling of the past rate of warming over the next four decades.



Note: This figure presents change in temperature across the United States. It is based on output from MAGICC/SCENGEN, which reports data in 2.5 degree grid boxes. Each grid box is approximately 150 miles across and contains an average change in temperature and precipitation for the entire grid box. The data are interpolated and smoothed to make them more presentable. Since the data are smoothed, transitions between different changes in temperature (and precipitation) should not be taken as being exact model output.

Figure I.5. Estimated increases in temperature (°F) in 2050 relative to 2010 using A1FI scenario, 3°C (5°F) sensitivity.

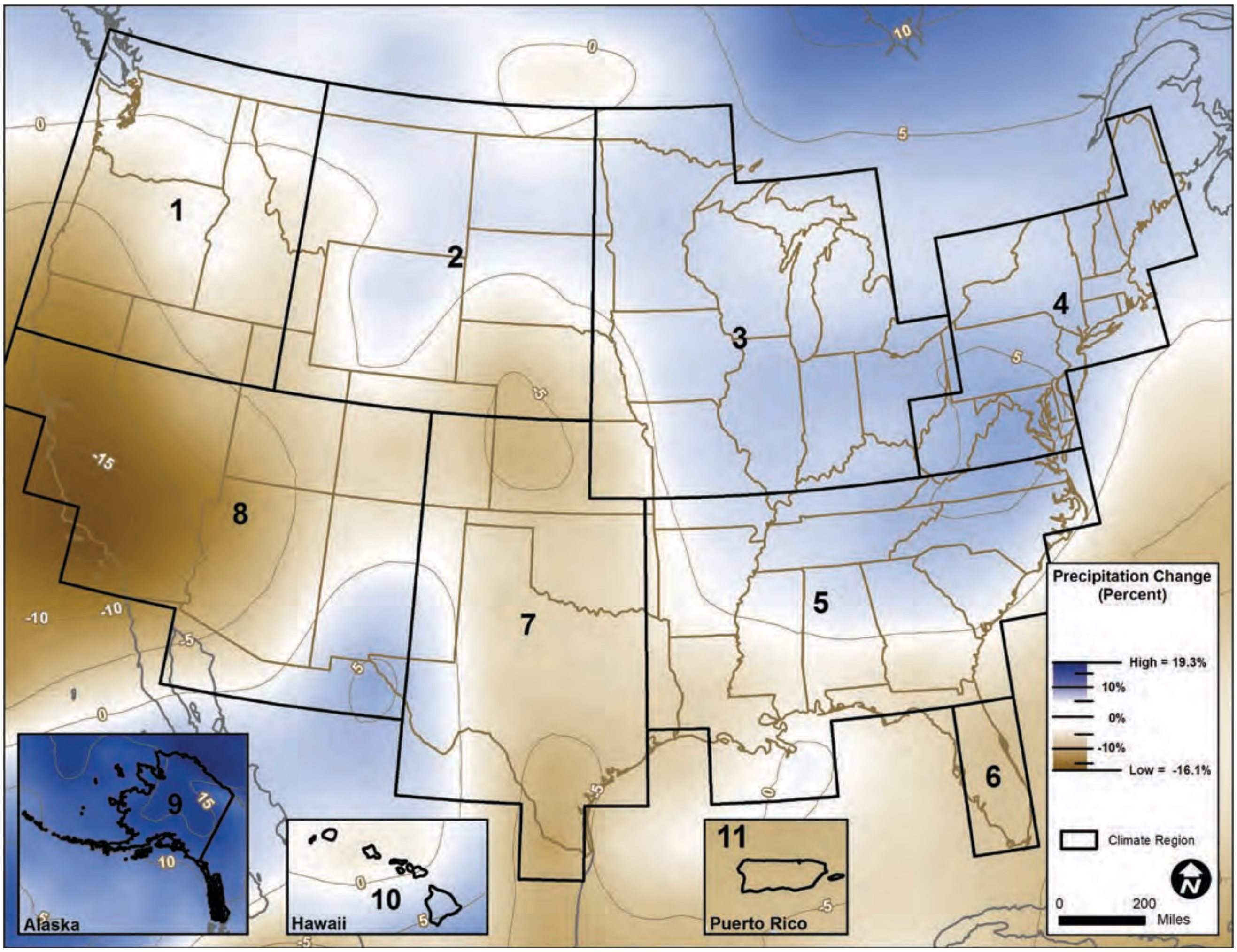
While all U.S. regions are projected to increase in temperature, the amounts will vary by location and season. In general, areas farther inland will warm more than coastal areas, because the relatively cooler oceans will moderate the warming over coastal regions. In addition, northern areas will warm more than southern areas because there will be less high-latitude snow cover to reflect sunlight. More warming is projected for northern and interior regions in the lower 48 states than for coastal and southern regions. Even though different emissions scenarios or different climate sensitivities would result in larger or smaller changes in temperature, the pattern of relative change (the most warming in interior northern areas, the least along the coasts and in southern areas) is unlikely to be different.

Precipitation/Drought

Average Annual Change

A rule of thumb on climate change is that changes in precipitation are much harder to project than changes in temperature for a number of reasons. One is that while average global precipitation will increase with higher temperatures (because as air warms it can hold more water vapor), it is not the case that all areas will get more precipitation. Some regions will get more precipitation and some will get less. Models and other information help to determine which areas are likely to become wetter and which ones are likely to get drier. In some areas, whether likely changes in average total precipitation will increase or decrease can be projected, but in other areas there is still too much uncertainty to project the change in direction of precipitation levels (Tebaldi et al. 2011). In addition, the atmospheric phenomena that govern precipitation are not modeled well in GCMs. "Convective" precipitation, e.g., summer thunderstorms, in particular, are not modeled well. These tend to happen at a small geographic scale and are not well simulated by GCMs or even RCMs. Even larger-scale processes such as the monsoons that typically happen in the summer in the Southwest are not simulated well by most GCMs.

In general, the models project, and observations also show, that the Northeast and Midwest are likely to become wetter while the Southwest is likely to become drier. In addition, all the climate models project an increase in precipitation in Alaska. It is not known whether precipitation will increase in other areas such as the Northwest or the Southeast. Figure I.6 displays average summer



Note: This figure presents change in precipitation across the United States. It is based on output from MAGICC/SCENGEN, which reports data in 2.5 degree grid boxes. Each grid box is approximately 150 miles across and contains an average change in temperature and precipitation for the entire grid box. The data are interpolated and smoothed to make them more presentable. Since the data are smoothed, transitions between different changes in precipitation (and temperature) should not be taken as being exact model output.

Figure I.6. Estimated percentage change in summer precipitation in 2050 relative to 2010 using A1FI scenario, 3°C (5°F) sensitivity.

Expected Climate Changes in Iowa

The *Iowa Climate Change Adaptation & Resilience Report* (U.S. EPA 2011) identified several changes that are likely to occur in Iowa's climate over the next 50 years. By 2065:

- "Springtime precipitation is expected to increase, resulting in heavier downpours.
- Stream and river flow may increase by 20 percent or more.
- Annual temperatures are expected to increase by 2.5 to 7.2°F."

The types and severity of hazards in Iowa are expected to change as well, including:

- "Flood hazards: Changes in precipitation and stream flow have already and will continue to increase the risk of riverine flooding, flash flooding, and damage due to expansive soils, especially during spring and early summer.
- Heat waves: Higher average temperatures will lead to more heat waves, resulting in more heat-related illnesses."

precipitation change from the model results. It may be best to look at regional areas in this figure and not focus on what is happening in specific states or localities. The exact transitions between the shaded areas should not be given much credence. They vary quite considerably from GCM to GCM. With such differences between the climate models, too much weight should not be put on individual model projections. The result of the averaging of models gives a more robust picture, but the existence of substantial intermodel differences implies that even the average is still subject to considerable uncertainty. So, while the models tend to show a drier Southwest and a wetter Northeast and Midwest, the differences across the models mean it is not possible to forecast exactly which localities become wetter or drier nor where the transitions between wet and dry areas lie.

Seasonal Change

Climate models tend to project *relatively* wetter winters and drier summers across most of the United States. This does not mean that all areas are projected to receive more precipitation in the winter and less precipitation in the summer. The results vary considerably model by model. As noted previously, the climate models do not simulate convective rainstorms well. This leads to high uncertainty about change in summer precipitation. Indeed, over the last 50 years, total precipitation over the lower 48 states increased in summer and winter (NCDC 2012). Natural variability may have a significant role in explaining this discrepancy. The models also project a larger increase in summer temperature than winter temperature.

Hurricanes and Other Extremes

Not only average conditions but the frequency and magnitude of extremes will also change. Indeed, infrastructure is often designed to withstand certain types and frequency of extremes such as extreme heat, precipitation, floods, or wind. The physics of climate change can tell us how certain types of extreme events will likely change:

- Extreme temperatures will get higher. As average temperatures increase so will extremes. This means that all locations will see increases in the frequency and duration of occurrence of what are now considered extreme temperatures, such as days above 32°C (90°F) or 35°C (95°F). How the variance (i.e., the standard deviation of daily, weekly, or monthly means) in temperatures will change is not clear. Some research suggests that blocking patterns could increase (e.g., Meehl and Tebaldi 2004). Also, where there is intense drought, temperatures can increase substantially.

- Number of freezing days will decline. As temperatures rise, the number of days that are below freezing will decrease. What is not known is how the number of days in which the high temperature is above freezing and the low temperature is below freezing will change in coming decades. In the long run, however, the number of days below freezing will decrease in many areas, particularly southern locations.
- Precipitation intensity will probably increase. Not only is average precipitation increasing, but the increases are also tending to come in the largest daily precipitation events (Groisman et al. 2005). The climate models also project increased precipitation intensity. Precipitation intensities (both daily and 5-day) are projected to increase almost everywhere with climate change, although the largest increases tend to happen in more northern latitudes (Tebaldi et al. 2006). This could result in increased flooding in some areas.

Tropical cyclones (e.g., hurricanes) will also change, but how they might change is complex. Hurricanes serve to transfer energy from lower latitudes to higher latitudes. What basically drives hurricanes is sea surface temperature. As sea surface temperatures rise, hurricanes can be expected to become more intense. As hurricane intensity increases (the lower the central pressure in a hurricane), so will the winds and precipitation.

But, hurricanes can also be affected by changes in the large-scale atmospheric circulation, such as wind shear (i.e., changes in the way wind speed and direction changes with altitude). Wind shear can break apart hurricanes. It is possible that wind shear could increase with climate change, which could reduce the total number of hurricanes. Recent research has suggested that there could be fewer hurricanes, but the ones that do occur, particularly the most powerful ones,

Expected Climate Change in Massachusetts

Much of the expected impact of climate change in the Massachusetts strategy relates to extreme weather events. Such events are expected to include high winds, hurricanes, storm surges, and waves that can damage energy infrastructure, ports, and buildings and reduce the capability of local agencies to provide emergency response. The plan also notes that extreme weather events in the Gulf Coast could affect natural gas supply in Massachusetts. Other impacts included (Executive Office of Energy and Environmental Affairs and the Adaptation Advisory Committee 2011):

- “With more frequent large storm events, damage to key infrastructure could become more frequent, take longer to repair, and entail more costly repairs and economic disruption.”
- “High temperatures and dense air conditions could increase runway length requirements to accommodate typically diminished aircraft performance in such weather situations.”
- “Massachusetts may not have sufficient alternative transportation modes and routes available in particularly sensitive locations to provide backup and continuity of service in responding to climate change effects.”

will be even stronger (Emanuel et al. 2008; Knutson et al. 2010). This suggests that over a timescale of decades, hurricanes could be more destructive, but there could be fewer of them. There is also substantial year-to-year and decade-to-decade variations in the projections of hurricane frequency (e.g., Landsea et al. 2012).

What about Sea-Level Rise?

Global sea levels are already rising mainly because of two factors. The first is thermal expansion of the oceans as they warm (higher temperatures expand liquids), and the second is the melting of glaciers, which transfers water from the land to the ocean. During the 20th century, global sea levels rose about 0.06 to 0.08 inch (1.5 to 2 millimeters) per year, but since the early 1990s have been rising at a rate of 0.12 inch (3 millimeters) per year. Given that rates of SLR can fluctuate naturally, it is not clear whether the apparent acceleration in the rate of SLR is the result of anthropogenic or natural causes (Bindoff et al. 2007).

Projections of future SLR vary widely. The IPCC projects that sea level will rise 8 inches to 2 feet (0.2 to 0.6 meter) by 2100 relative to 1990 (Solomon et al. 2007). This projection, however, only partially accounts for the potentially significant melting of major ice sheets in Greenland and West Antarctica (Oppenheimer et al. 2007). Each of these ice sheets contain enough water to raise sea levels 23 feet (7 meters) or more, but it would take centuries to millennia for that amount of SLR to occur, should these major ice sheets melt.

Several studies published since the IPCC Fourth Assessment Report estimate that sea levels could rise 5 to 6.5 feet (1.5 to 2 meters) by 2100 (e.g., Pfeffer et al. 2008; Vermeer and Rahmstorf

Expected Impacts of Climate Change in California

According to the state's adaptation plan, it is expected that less extreme cold days will reduce frost heave and road damage, but "extreme hot days (including prolonged periods of very hot days) are likely to become more frequent, increasing the risk of buckling of highways and railroad tracks and premature deterioration or failure of transportation infrastructure" (California Natural Resources Agency 2009). The California Department of Transportation foresees increased damage to transportation infrastructure as a result of flooding of tunnels, coastal highways, runways, and railways and the related economic consequences of such disruptions. Also noted in the plan, "the combination of a generally drier climate in the future, which will increase the chance of drought and wildfires, and the occasional extreme downpour, is likely to cause more mud- and landslides which can disrupt major roadways and rail lines. The related debris impacts are historically well known to California, but if they become more frequent, will create greater costs for the state and require more frequent repair" (California Natural Resources Agency 2009). The plan notes that SLR will most likely be of greatest concern over the long term affecting ports, coastal roads and airports, in particular. The three San Francisco airports—San Francisco, Oakland and San Jose—are each near sea level. Approximately 2,500 miles of roads and railroads are at risk from coastal flooding and it is expected that SLR might require "entirely new drainage systems in low-lying cities with drainage that is pump-driven rather than gravity-driven" (California Natural Resources Agency 2009).

2009). Pfeffer et al. (2008) conclude that the most likely increase in sea levels by 2100 is 2.6 feet (0.8 meter) relative to 1990 and that SLR will not exceed 6.6 feet (2 meters) by 2100. A recently released report by the National Research Council projects that mean sea level will rise 3.1 to 9 inches (0.08 to 0.23 meter) by 2030 relative to 2000, 7 to 18.5 inches (0.18 to 0.48 meter) by 2050, and 19.6 to 55 inches (0.5 to 1.4 meters) by 2100 (Committee on Sea Level Rise in California, Oregon, and Washington 2012). Using MAGICC (Wigley 2008), a scenario yielding 31.5 inches (0.8 meter) SLR by 2100 would have approximately 10 inches (0.25 meter) of SLR by 2050 relative to 1990 [8 inches (0.2 meter) relative to 2010].

Note that the SLR expected at specific coastal locations can vary considerably from place to place and from the global mean rise because of two factors. First, the rise can vary because of differences in ocean temperatures, salinity, and currents. These factors can cause relative regional SLR to vary by as much as half a foot (0.15 meter) (Meehl et al. 2007; Bamber et al. 2009).

The second factor and, of perhaps greater importance for relative SLR at a particular location, is the subsidence or uplift of the coast itself. The weight of glaciers that covered much of the northern hemisphere tens of thousands of years ago lowered the land below them as well as the land for many hundreds of miles around the periphery of the ice sheets. As the glaciers retreated, the land rose (uplift). This is particularly the case in northern areas, especially in Alaska. Many other coastal areas are sinking (subsiding) because the pumping of groundwater and the damming of rivers has reduced sedimentation in deltas such as in the Mississippi River delta. One of the most dramatic examples of subsidence is in Louisiana, where land is subsiding at a rate of approximately 3 feet (0.9 meter) per century. Also, shifts in the Earth's tectonic plates can cause either uplift or subsidence in coastal areas. Appendix A lists projections of change in sea level by state, taking into account subsidence and uplift.

Where Are Climate Data and Advice Available for a Specific State?

Most states have state climatologists, which can be a resource for state DOTs, and many states have universities with centers of research and expertise in climate issues, which can also be a valuable resource. For those states interested in developing a systematic approach toward climate adaptation and the state's transportation network, it is important that partnerships with these groups be developed.

The following sections identify data sets that are publicly available. The advantages and limitations of downscaling were discussed earlier. It is worth repeating that while downscaling can appear to provide more accuracy because projections are at a higher resolution, it is often the case that downscaled projections are no more reliable than projections from GCMs.

General Circulation Model Data

GCM data may be obtained from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at the Lawrence Livermore National Laboratory in California (http://www-pcmdi.llnl.gov/). PCMDI includes data from the Coupled Model Intercomparison Project 3 (CMIP3), which is the set of GCM scenarios run for the IPCC Fourth Assessment Report published in 2007 (Solomon et al. 2007). PCMDI is collecting GCM scenarios being run for the Fifth Assessment Report (CMIP5).

A simpler approach is to use MAGICC/SCENGEN, the tool that was used in this research. It provides parameterized output based on GCMs, not raw GCM projections, and can be obtained at http://www.cgd.ucar.edu/cas/wigley/magicc/.

Bias-Corrected Statistical Downscaling

It is generally *not* a good idea to use raw GCM output directly as an estimate of climate change. Typically *change in climate* as estimated by GCMs is used. The increase in temperature or change in precipitation estimated by the models can be combined with observed climate data sets to create a climate change scenario (e.g., Fordham et al. 2011). (Typically temperatures are added to observations and percentage change in precipitation is multiplied by observed precipitation.) This approach corrects for the difference or "bias" between simulated GCM representation of current climate and observations. The U.S. Bureau of Reclamation has applied an approach called "bias-corrected statistical downscaling," which corrects for the bias in simulating current 1/8th degree resolution across the lower 48 states and then applies the bias correction to projections of future change in climate. The bias is assumed to remain unchanged in the projections of future climate. The Bureau has applied this approach to 16 GCMs at several different future time periods and made the data publicly available. These data may be downloaded at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html.

Regional Climate Model Data Sets

RCMs are very complicated and expensive to run. However, the North American Regional Climate Change Assessment Program (NARCCAP) is being run from the National Center for Atmospheric Research in Boulder, Colorado. NARCCAP is running six RCMs using outputs from four GCMs to provide a wide array of downscaled climate projections. Data may be obtained at http://www.narccap.ucar.edu/.

Another option for regional climate change modeling is to obtain and run the United Kingdom Meteorological Office regional climate modeling tool called PRECIS. Running this tool will take more time and effort than just using output from regional climate modeling exercises such as NARCCAP. Also note that PRECIS is driven by one GCM (the UK Hadley model) rather than several GCMs. PRECIS can be obtained at http://www.metoffice.gov.uk/precis.

There are no national data sets derived by applying statistical downscaling techniques. One version of the statistical downscaling method is employed in the user-friendly software SDSM, which may be obtained at http://co-public.lboro.ac.uk/cocwd/SDSM/ from Loughborough University in the United Kingdom. The downscaling technique will need to be mastered in order to run the model and produce downscaled estimates of climate change, although applying SDSM will probably take less time than running PRECIS.

What Needs to be Known about Climate Forecasting with Models?

Generally, individual climate model runs have been used as emissions scenarios. A scenario should be plausible but need not have a high probability or any probability associated with it. Each model run assumes a specific GHG emissions scenario. As noted previously, even with the same assumptions about GHG emissions, different climate models will give different projections of change in global and regional climate. Each climate model run is assumed to be a *plausible* estimate of how climate *could* change. Since there is so much variation across the emissions scenarios and the models, the best that can be offered is a suite of climate change scenarios (climate model runs) for estimating potential impacts.

A useful rule of thumb is to apply a range of scenarios to capture a reasonable range of uncertainty about future climate. It is important to capture such a range on variables that are particularly important such as precipitation and temperature. So, if the agency is most concerned about how precipitation can change, then it should use scenarios that capture a wide range of potential changes in precipitation.

Timeframe

Climate conditions over approximately the next two to three decades will most likely be dominated by natural variability, whereas more than three decades into the future, the "signal" from human-caused climate change will most likely emerge from the "noise" of natural variability. What this means is that it generally does not make sense to use outputs from climate models to project climate conditions less than three decades from now. For these shorter timescales, historical climate information averaged over recent decades could be used. Essentially doing this takes advantage of the fact that, over the next two to three decades, the signal of anthropogenic climate change is small relative to the magnitude of natural climatic variability.

To get estimates of how climate more than two to three decades from now may change, climate models should be used. Note that the outputs from the climate models are typically long-term averages of climate. A "climate" is defined as an average of 20 to 30 years of observations. So, for example, the observed period 1981–2010 is used to define current climate. A projection of a future period, say 2060, should rely on model projections averaged over 20 to 30 years surrounding 2060, e.g., 2051–2070 or 2046–2075.

Climate models project future climate on a sub-daily basis. Using sub-daily data, even daily data, is very complicated. To make things much easier, average monthly changes in variables such as temperature and precipitation from the models are typically used. These can be combined with an observed data set to simulate natural variability. Changes in temperature and precipitation (and other variables) simulated by a model could be combined with historical observations, say from 1981 to 2010 as discussed in the previous paragraph. This procedure assumes the variability in climate over recent years will continue in the future, but, at least in a general sense, whether the climate will be warmer, wetter, or drier on average can be projected.

Emissions Scenario

As noted previously, the future levels of GHG emissions are unknown. It is not possible to reliably predict future population growth, economic activity, technological development and GHG-related policies. Many studies have used the A1B, A2, and A1FI SRES scenarios to estimate how climate may change if future GHG emissions generally are not controlled (e.g., Karl et al. 2009). In the absence of a strict policy scenario, some have used the B1 scenario as a proxy for such a scenario. The RCPs 6.0 and 8.5 represent a range of future climate conditions that is consistent with the SRES scenarios, except for B1. RCP 4.5 is roughly similar to the B1 scenario. RCP 2.6 represents a more extreme policy scenario where it is assumed that radiative forcing rises to a peak around 2050 and then slowly declines. So, there is no SRES scenario that can serve as a close neighbor to RCP 2.6.

As was seen in Table I.2, the A1FI, A2, and A1B SRES scenarios do not differ substantially in CO_2 concentrations or temperature change in 2050. By 2100, they do differ substantially from each other. So if examining the consequences of unmitigated climate change by 2050 is important, the choice of an emissions scenario is not that critical. The consequences will probably not be substantially different across the unconstrained emissions scenarios. That suggests that the use of one unconstrained emissions scenario for time periods up to 2050 is reasonable. Beyond 2050, it may be prudent to use more than one emissions scenario if possible. An important reason for using a wide range of emissions scenarios is to find out how the system could be affected by different magnitudes of climate change.

Climate Models

It is not advisable to use just one climate model. For a given emissions scenario, a model only gives one projection of change in climate, which can be misinterpreted as a forecast. That can be particularly misleading given the uncertainties with regional climate change.

Given the wide range of potential changes in temperature, but particularly precipitation, it is critical that at least several scenarios be used to encompass a reasonably wide range of possible changes in climate. It is widely felt that a range of projections in regional climate across a number of climate models gives the minimum range of uncertainty about how regional climate can change.

Some advocate first examining how well models simulate current (observed) climate and eliminating the models that perform the worst (see Fordham et al. 2011). Current models tend to do a decent job simulating temperature patterns. It is in simulating current precipitation patterns that performance levels differ markedly; therefore, using the models' accuracy in simulating observed precipitation to weed out the worst-performing models would be appropriate. Model quality can be assessed in two ways: (1) by examining how well the model simulates current (observed) climate and (2) by determining whether the model's projections are consistent with other models. Models that simulate current climate poorly or that give projections that differ *strikingly* (not by a relatively small amount) from all other models (i.e., "outliers") should probably be eliminated from consideration.

Models should be selected that give a wide range of change in precipitation, e.g., the wettest and driest models. Whether these models capture a wide range of change in temperature should also be considered. This approach will only capture the extremes. Including a model that simulates a change in climate in the middle of the precipitation and possibly temperature distribution is also advisable. The three models would then capture wet, middle, and dry conditions.

Another option is to use the average of models' simulation of changes in climate to capture middle conditions. One argument for using the model average is that the average often agrees better with observed climate than any individual model estimates (Reichler and Kim 2008). This is, however, not always the case and tends to be less so for smaller regions (i.e., it is generally true at continental to global scales, but may not be the case at the level of individual states). Furthermore, skill at simulating present-day climate does not translate to skill at projecting future climate—which is why a range of model results should be considered.

In summary, three scenarios of change in climate should be used to capture a range of potential conditions. These scenarios should include a relatively wet model run, relative dry model run, and either a single model run in the middle of the distribution or an average of all of the models. Several emissions scenarios may also need to be run, particularly if change in climate in the latter half of this century is being examined, so as to gain understanding in how climate change impacts could differ.

CHAPTER 4

Possible Impacts to the Highway System and the Natural Environment and Agency Responses to Them

This chapter identifies potential climate change impacts on highway systems and on the natural environment, and the possible strategies state transportation agencies could adopt to respond or prepare for these impacts. For the highway system, information is presented on the climate-related impacts on infrastructure, operations, and maintenance. The climate stressors examined in this chapter include changes in temperature, precipitation, sea-level rise, and hurricanes. A tabular summary of expected impacts is located at the end of the chapter.

How Could Changes in Temperature Affect Road Assets?

As discussed in Chapter 3, average temperatures are likely to increase throughout the United States over the coming decades. However, relative increases will be higher in northern and inland areas.

Change in Extreme Maximum Temperature

The literature points to a likely increase in very hot days and heat waves. Heat extremes and heat waves will continue to become more intense, longer lasting, and more frequent in most regions during this century. Increasing periods of extreme heat will place additional stress on infrastructure, reducing service life and increasing maintenance needs.

Impacts on Highway Infrastructure

Extreme maximum temperature and prolonged-duration heat waves are expected to lead to premature deterioration of infrastructure. Temperature increases have the potential to affect and reduce the life of asphalt road pavements through softening and traffic-related rutting. Extreme heat can also stress the steel in bridges through thermal expansion and movement of bridge joints and paved surfaces.

Impacts on Operations/Maintenance

The increase in very hot days and extended heat waves is expected to affect highway operations and maintenance in several ways. The first is the probable limit on construction activities and the number of hours road crews can work due to health and safety concerns for highway workers. The increase in extreme heat could also lead to load restrictions on roads. Pavement damage and buckling will disrupt vehicle movements. Extreme heat could disrupt vehicle operations because of overheating and increased risk of tire blowouts in heavily loaded vehicles. Higher temperatures could lead to an increased need for refrigerated freight movement, and thus result indirectly in higher transportation costs.

A secondary impact of extreme and extended periods of heat, when combined with reduced precipitation, is the projected increased risk of wildfires and resulting smoke, especially in the west. Fire poses a risk to infrastructure and travelers, and can result in road closures.

Change in the Range of Maximum and Minimum Temperatures

Changes in the projected range of temperatures, including seasonal changes in average temperatures, can also affect highway systems. The increased temperature ranges will likely benefit highways in some ways, while increasing risks in others.

Impacts on Highway Infrastructure

The length of the season when it can snow will decrease, but winter precipitation is projected to rise. So there could be more snow during the shorter season, i.e., individual snow storms could be bigger. Warmer winters will likely lead to less snow and ice on roadways than occurs today, but may possibly increase the incidence of slippery roads, while the incidence of frost heave and road damage caused by snow and ice in southern locations is likely to decline. However, warmer winters may also lead to an increase in freeze–thaw conditions in northern states, creating frost heaves and potholes on road and bridge surfaces that increase maintenance costs. Pavements built on expansive clays, in particular, will see the subsurface expand or contract significantly given extended periods of wet weather or drought. Repairing such damage is already estimated to cost hundreds of millions of dollars in the United States annually.

The effects of changing temperatures are particularly apparent in the Arctic regions. Warming winter temperatures, especially in the high northern latitudes of Alaska, could cause the upper layer of permafrost to thaw. Over much of Alaska, the land is generally more accessible in winter, when the ground is frozen and ice roads and bridges formed by frozen rivers are available. Winter warming would therefore shorten the ice road season and affect access and mobility to northern regions. Thawing permafrost could also damage highways as a result of road base instability, increased slope instability, landslides, and shoreline erosion. Permafrost melt could damage roads and bridges directly through foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost) or indirectly through landslides and rock falls. In addition, hotter summers in Alaska and other mountainous western locations lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.

Expected Climate Impacts in Washington State

The Washington State DOT realizes that climate change "may alter the function, sizing, and operations" of the state's facilities. To ensure that its system can function as intended over 50, 70, or 100 years, facilities "should be designed to perform under the variable conditions expected as a result of climate change. For example, drainage culverts may need to be resized to accommodate more intense rainfall events or increased flows due to more rapid glacial thawing." Areas expected to see the greatest impact include locations "in the mountains, either above or below steep slopes, in low-lying areas subject to flooding, along rivers that are aggrading due to glaciers melting, and in low-lying coastal areas subject to inundation from sea-level rise." (WSDOT 2012)

In Southern Canada, studies suggest that rutting and cracking of pavement will be exacerbated by climate change and that maintenance, rehabilitation, or reconstruction of roadways will be required earlier in the design life (Mills et al. 2009). Similarly, simulations for pavements in Alberta and Ontario show that temperature increases will have a negative impact on the pavement performance in the Canadian environment (Mills et al. 2009). As temperature increases, accelerated pavement deterioration due to traffic loads on a warmer pavement was expected and observed. An increase in temperature would facilitate rutting because the pavement is softer. Pavement movement due to loads on a softer pavement would also result in increased cracking. Overall temperature changes significantly affected the level of pavement distress for the international roughness index (IRI), longitudinal cracking, fatigue cracking, asphalt concrete deformation, and total deformation.

Impacts on Operations/Maintenance

The change in range of maximum and minimum temperatures will likely produce both positive and negative impacts on highway operations/maintenance. In many northern states, warmer winters 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.

On the other hand, with warmer winter temperatures, greater vehicle load restrictions may be required to minimize damage to roadways if they begin to subside and lose bearing capacity during the spring thaw period. With the expected earlier onset of seasonal warming, the period of springtime load restrictions might be reduced in some areas, but it is likely to expand in others with shorter winters but longer thaw seasons.

How Could Changes in Precipitation Affect Road Assets?

Changes in Overall Precipitation

Changes in precipitation—both rain and snow—will vary widely across the various regions in the United States. These changes are expected to affect highways in several ways, depending on specific regional precipitation levels and geographic conditions. And with 20 percent of the United States reportedly in extreme drought and 60 percent in some degree of it, drought is also a concern to transportation officials.

Impacts on Highway Infrastructure

In areas with increased precipitation, there is greater risk of short- and long-term flooding (e.g., more spring floods in the upper Midwest). In other areas, more precipitation may fall as rain rather than snow in winter and spring, increasing the risk of landslides, slope failures, and floods from the runoff, which can cause road washouts and closures. In addition, northern areas are projected to have wetter winters, exacerbating spring river flooding. In other areas, the increase in precipitation could lead to higher soil moisture levels affecting the structural integrity of roads, bridges, and tunnels and leading to accelerated deterioration.

If soil moisture levels become too high, the structural integrity of roads, bridges, and tunnels, which in some cases are already under age-related stress and in need of repair, could be compromised. Standing water can also have adverse impacts on the road base. Overall, the increased risk of landslides, slope failures, and floods from runoff will likely lead to greater road repair and reconstruction needs.

Impacts on Operations/Maintenance

Changes in rain, snowfall, seasonal flooding, and drought conditions can affect safety and maintenance operations on roads. More precipitation increases weather-related crashes, delays, and traffic disruptions and, consequently, loss of life and property. In New York City and other urban areas, precipitation-related impacts may include increased street flooding and associated delays and an increase in risk of low-elevation transportation flooding and water damage. Increases in road washouts and landslides and mudslides that damage roads are expected.

Climate models tend to show wetter winters but drier summers in most parts of the country. Dry summers or droughts can lead to increased wildfires, which could threaten roads and other transportation infrastructure directly or cause road closures due to reduced visibility. According to the U.S. Global Change Research Program, longer periods of extreme heat and drought in summer will damage roads in several ways, including "subsidence of roadbeds and softening of asphalt that leads to rutting from heavy traffic. Sustained air temperature over 90°F is a significant threshold for such problems. Extreme heat can cause deformities in rail tracks, at minimum resulting in speed restrictions and, at worst, causing derailments. Air temperatures above 100°F can lead to equipment failure. Extreme heat also causes thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs. Vehicle overheating and tire deterioration are additional concerns" (U.S. Global Change Research Program Impacts 2011).

Areas with both wetter winters and drier summers may be particularly at risk, as wetter winters may promote increased springtime vegetation growth, in turn providing more fuel for summer wildfires. There is also increased susceptibility to mudslides in areas deforested by wildfires, particularly if wintertime precipitation increases.

Increased Intense Precipitation

Heavier rainfall downpours and more intense storms are very likely to become more frequent in widespread areas of the United States. This intense precipitation has immediate effects on highway operations and over the long term could change ecological systems that ultimately influence highway design and operations/maintenance.

Impacts on Highway Infrastructure

In areas with heavy winter rain, mudslides and rockslides can damage roads from washouts and undercutting and lead to permanent road closures. For example, winter rain has caused yearly washouts of Highway 1 in California (Peterson et al. 2008). Heavy precipitation and increased runoff during winter months are likely to increase the potential of flooding to tunnels, culverts, and coastal highways. In the future, the combination of a generally drier climate in the southwest (which will increase the chance of drought and wildfires) and more frequent extreme downpours (and occasionally wet winters) is likely to cause more mud- and landslides that can disrupt major roadways. In California, the removal of the debris generated by intense storms has become a major operations cost and will likely become even greater in the future (Peterson et al. 2008).

An Australian study found that in Victoria the projected increase in the frequency and intensity of extreme rainfall events has the potential to cause significant flood damage to roads—especially tunnel infrastructure—due to acceleration in the degradation of materials, increased ground movement, changes in groundwater affecting the chemical structure of foundations, and fatigue of structures from extreme storm events. Bridges are more prone to extreme wind events and scouring from higher stream runoff, and bridges, signs, overhead cables, and tall structures face increased risk from greater wind speeds.

Scottish Road Network Landslide Study: Implementation Report

This report focuses on assessing and ranking the hazards presented by debris flow. Scotland's hazard assessment involves mapping areas of the road network that are vulnerable to flow paths. This desk exercise is supplemented by site-specific inspections with a hazard score for each site of interest. The hazard ranking process also takes into consideration the socioeconomic impact of debris flow events. The end result is a list of high-hazard sites in Scotland where the road network is vulnerable to debris flow. Once these hazard sites are identified, they are monitored and at some point warning signs may be installed, the road closed, or traffic diverted. In the long run, adaptation may include measures to protect the road such as installing barriers, engineering to reduce the opportunity for debris flows, or road realignment (Winter et al. 2005).

Impacts on Operations/Maintenance

Generally, intense precipitation and increased runoff during winter months are likely to increase flood damage to tunnels, culverts, and coastal highways. The intense downpours can also lead to more landslides and affect roadway operations. The number of road closures due to flooding and washouts will likely increase, as will the potential for extreme incidents of erosion at project sites as more rain falls over shorter periods.

The increase in heavy precipitation will inevitably cause increases in weather-related crashes, delays, and traffic disruptions in a network already challenged by increasing congestion. There will be potential flooding of evacuation routes and construction activities will be more frequently disrupted.

How Could Sea-Level Rise Affect Road Assets?

Sea levels will continue to rise as a result of thermal expansion and the possible loss of mass from ice sheets.

Impacts on Highway Infrastructure

Infrastructure in coastal areas is expected to be heavily affected by rising sea levels, often compounded by regional subsidence (the sinking of a land mass due to compaction of sediments or tectonic forces). Coastal highways are at risk from the combination of rising sea levels along with a heightened coastal flooding potential from tropical and non-tropical storms. Many state DOTs cite the impacts associated with SLR as being the most important challenge they face. An estimated 60,000 miles of coastal highway in the United States are already exposed to periodic flooding from coastal storms and high waves (Karl et al. 2009). Along with the temporary and permanent flooding of roads and tunnels, rising sea levels and storm surges will likely cause erosion of coastal road bases and bridge supports. Note that storm surge risks related to hurricanes will be discussed in more detail in the next subsection.

In addition to more frequent and severe flooding, underground tunnels and other low-lying infrastructure may also experience encroachment of saltwater, which can lead to accelerated degradation of infrastructure. This can reduce the structure's life expectancy, increase maintenance costs as well as the potential for structural failure during extreme events. Underground tunnels and other low lying infrastructure will experience more frequent and severe flooding. Higher sea levels and storm surges may also erode the road base and undermine bridge supports. The loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action.

Impacts on Operations/Maintenance

As coastal roads are flooded more frequently and for longer periods of time, road closures may become longer and the cost of repair may rise. These affected roads may need to be protected by raising or relocation. The significance of the vulnerability of coastal roads is compounded by the function of many of them as evacuation routes during hurricanes and other coastal storms. These routes could become seriously compromised and lead to evacuation route delays and stranded motorists.

How Could Greater Hurricane Intensity Affect Road Assets?

The intensity of the most powerful hurricanes is projected to increase, with larger peak wind speeds and more intense precipitation. The number of Category 4 and 5 hurricanes is projected to increase, while the number of less powerful hurricanes is projected to decrease. Three aspects of hurricanes are relevant to transportation: precipitation, winds, and wind-induced storm surge. Stronger hurricanes have longer periods of intense precipitation, higher wind speeds (damage increases exponentially with wind speed), and higher storm surge and waves. Increased intensity of strong hurricanes could lead to more evacuations, infrastructure damage and failure, and interruptions in transportation service. The prospect of an increasing number of higher category hurricanes has serious implications for the highway system.

Impacts on Highway Infrastructure

Roads are likely to face increased flooding in the aftermath of strong hurricanes. Prolonged inundation can lead to long-term weakening of roadways. As a result of Hurricane Katrina, some pavements showed that they suffered a permanent strength loss equivalent to 2 inches of pavement (Gaspard et al. 2007).

Roads and bridges can be damaged during hurricanes by wave battering (from water driven inland by storm surge) and high winds. Concrete bridge decks weighing many tons can literally be blown or floated off their supports during hurricanes, as seen during Hurricanes Katrina and Rita. The widespread damage to highways from these hurricanes illustrated the powerful effects of these intense tropical storms. Damage to signs, lighting fixtures, and supports are also products of hurricane force winds.

Impacts on Operations/Maintenance

More intense storms will leave behind greater volumes of debris and can cause road closures and disruptions. Damage to highway networks caused by the storms increases the challenge for system operations and emergency management. In addition, there will be more frequent and potentially more extensive emergency evacuations, placing further strain on highways. At the same time, SLR may render existing evacuation routes less useable in future storms.

How Could Climate Stressors Affect Ecological Systems?

In addition to the direct effects on highways, climate change will likely affect ecological systems as well. Highway infrastructure interacts with ecosystems in a number of different ways. Highway construction can affect ecosystems by displacing natural environments, such as wetlands. Roads can act as a barrier, restricting the movement and migration of flora and fauna, fragmenting ecosystems, and changing the natural flow of water across the right-of-way. Roads can also be a local source of pollution and damage water bodies, as with the pollutants such as oil that run off roads with rainfall. Transportation professionals have worked for years with resource agencies and ecologists to understand these interactions and develop strategies to reduce or mitigate the negative effects of highways on ecosystems—and to identify opportunities to restore and strengthen compromised environments.

However, climate change will present new challenges to ecological protection and restoration, by affecting the assumptions of ecological conditions under which a road system is built and designed. In addition, many state transportation agencies agree to maintain the functionality of replacement wetlands in perpetuity. How is this commitment compromised by changes in the wetland that are caused by changes in the climate? Some of the changes to ecosystem processes that will likely be relevant for transportation include the following (Karl et al. 2009):

- Large-scale shifts in the ranges of species and the timing of the seasons and animal migration
- Increases in fires, insect pests, disease pathogens, and invasive weed species
- Hotter, and drier, deserts and dry lands
- Coastal and near-shore ecosystems, already under multiple stresses, made more vulnerable by ocean acidification
- Potential contraction of the habitats of some mountain species and cold water fish.

Changing climatic conditions can affect the nature and severity of the ecological impacts of a road and can also change the effectiveness of mitigation measures that have been put in place to reduce ecological harm. For example (Karl et al. 2009):

- Coastal ecosystems—As sea levels rise, coastal ecosystems will migrate inland. Coastal highways can serve as a barrier to this migration, especially where the road is armored against rising sea levels. As a result, coastal ecosystems will be squeezed between retreating shores and immobile highway right-of-way, in some cases eventually disappearing. (Some states, such as Massachusetts and Rhode Island, prohibit shoreline armoring along the shores of some estuaries so that ecosystems can migrate inland, and several states limit armoring along ocean shores.)
- Runoff—Changes in precipitation patterns will affect the magnitude and ecological impact of stormwater runoff. More intense precipitation events in areas of high impervious cover could result in runoff spikes that can cause increased erosion in streambeds and, in warm weather, thermal shock to water bodies from the sudden infusion of pavement-heated runoff. It may also result in pollutant loading spikes, particularly if rainfall events become less frequent. On the other hand, decreased use of snow and ice chemicals in wintertime will reduce the harmful effects of these chemicals on water bodies.
- Wildlife movement—Roads can act as barriers to wildlife movement and migration, either by preventing movement (e.g., walls and fences) or by increasing the risk of injury and mortality while crossing roadways. As climate changes, species may need to relocate to areas that have appropriate climatic conditions and resources. Facilitating wildlife movement under climate change can be achieved through mitigation measures that have already been developed. For example, warning signage for motorists and wildlife passageways ("critter crossings") have been developed to make road crossings more manageable for wildlife, often after detailed studies of local animal movements; the locations for these crossings may need to be adjusted to accommodate future animal movement patterns. Similarly, the design and placement of culverts, which is critical for maintaining aquatic habitats in streams and waterways that cross highway right-of-way, may also not be optimized for future precipitation and hydrologic patterns. Culverts may need to be redesigned to accommodate new precipitation regimes and to allow aquatic organisms to pass unimpeded.

- Roadside vegetation—Current practices for maintaining or controlling roadside vegetation for a given region may not be well adapted to future climates. For instance, current roadside vegetation may not persist or may be more prone to fire under drier climate conditions.
- Invasive species—As changing climate conditions render the "native" species less suited for a given region, invasive (non-indigenous) species will become much more difficult to control. In some cases, native species may become more vulnerable both to current and novel invasive species.
- Wetland mitigation/restoration—Replacing wetlands affected by highway project construction is an accepted part of project mitigation. Doing so might be exacerbated by a changing climate, which would require designing wetlands that function in both the current and future climates.

Tropical Storm Irene's Impact on Vermont

Vermont was one of the states affected by Tropical Storm Irene. According to the Vermont Agency of Natural Resources, rainfall totals of 3 to 5 inches were recorded throughout the state, with many areas receiving more than 7 inches, especially on higher, eastern slopes. Hundreds of roads were closed; utilities were washed out; many towns were isolated because of washed-out roads; a half-mile stretch of the major east-west state highway washed away; 35 bridges were destroyed; 960 culverts were damaged; and 200 miles of state-owned railroads were closed with 6 railroad bridges impassable. Interestingly, in 2007 the Vermont Agency of Transportation, the state's DOT, had identified what turned out to be prophetic predictions of what might occur in Vermont with changes in climate and weather. The list (updated after Tropical Storm Irene) included the following (Vermont Agency of Transportation 2012):

- Flooding and erosion of low-lying roads, railroads, and other infrastructure
- With changes in the intensity and frequency of storm events, the need for culverts, bridges, erosion controls, and stormwater systems to be designed and maintained to adequately handle the associated increased flow, sediment, and debris transport
- Increased bridge scour from increased stream flow
- Increased moisture and corrosion damage on pavements and structures
- Failure of pavement and bridge expansion joints
- The effects on roadbed and pavement longevity from an increase in freeze–thaw cycles
- Increased pavement rutting and vehicle hydroplaning potential
- Increases in extreme wind events and associated downed trees, power lines, and debris blocking roadways, waterways, and right-of-way; also higher wind loading on bridges
- Increased emergency preparedness and evacuation demands
- Changing winter maintenance demands due to more or less snow or an increase in freeze events
- Compromised availability and the need to stockpile diesel fuel, salt, and sand
- Effects of new exotic species and longer growing season on right-of-way vegetative management and stream bank longevity

The impacts of climate change on the natural environment could necessitate a number of adjustments by highway planners, designers, and operators. Some of these changes will include the following:

- Highway planners and designers will have to give more consideration to future changes and conditions before making decisions. Historic or current conditions will not likely be indicative of future conditions.
- The numbers and types of endangered species will likely change in the future because of climate change. For example, some species that are endangered today may become more plentiful in the future and some species that are plentiful today may become more endangered.
- Careful planning will be needed in wetland banking. Current wetland banks may dry up as some regions become more arid. Even areas with increased precipitation may become drier because of increased heat and evaporation. Continuing to expand current wetlands in some regions may not be an option in the future.
- Locations where wildlife cross highways will change as certain species move to higher altitudes and more northern latitudes. Careful thought will need to go into deciding where to locate future crossings.
- Guidelines for the construction and restoration of roadside vegetation will need to change in the future as areas become warmer and more arid. Current guidance on vegetation management recommending the use of native plants in roadside plantings may need to be revised since native plants may not survive in future climatic conditions. Also, careful consideration will need to be given to potential roadside fires when vegetation and trees die.
- Highway maintenance labor and costs will likely increase with more mowing and herbicide treatments of invasive species.
- In areas with increased precipitation, highway agencies will need to respond to increased stormwater runoff and flooding. Designers in the Midwest and Northeast will need to consider larger culverts and bridges. Also, the increase in the amount of runoff will impact the quality of the water and the need for expanding treatment facilities.
- With rising sea levels and the concern about certain species being unable to migrate inland, the construction or reconstruction of coastal highways will need careful reconsideration.

What Are the Types of Adaptation Strategies that Can Be Considered by Transportation Agencies?

Once possible impacts of climate stressors are identified, transportation officials should consider possible actions to avoid, minimize, or mitigate potential risks. The types of strategies to be considered relate to both the types of impacts expected and the level of funding available for protective action. Table I.4 lists a range of goals and supporting actions that can be considered for both operations/maintenance and design functions, as provided by the Maryland State Highway Administration (2012). Note that Maryland's *Climate Change Adaptation Policy* contains information for each action that includes the following:

- **Climate threats**, including
  - High temperature extremes,
  - Floods,
  - Sea-level rise,
  - Slope failure,
  - Tropical storm,
  - Wind, and
  - Winter storms.

Table I.4. Actions listed in Maryland's climate change adaptation policy.

Goal	Actions
Take operations, maintenance, and administrative actions now which enhance the response to and prevent impacts from extreme weather events	***Response Actions*** • Enhance coordination with counties on detour routing and signal timing • Install system that automatically adjusts signal timing to traffic conditions on key detour routes • Provide GPS-capable devices to all snow plows • Provide GPS-capable devices for maintenance crews and implement digital work orders • Enhance cross-training in emergency maintenance tasks • Install battery backups at all intersections that would require a traffic officer if there was an outage • Implement an automated system for detecting stoplights affected by power outages • Designate truck parking areas during snowstorms and convey information to truck drivers • Install system that adjusts signal timing to road conditions on major arterials • Expedite environmental permitting to allow drainage emergencies to be quickly addressed (general permitting) • Incorporate more contingency clauses in construction contracts for extreme weather events • Enhance real-time interaction between maintenance crews in the field and engineers prior to repairs • Preposition equipment and conduct inspections before predicted extreme rainstorms • Enhance coordination with utilities on at-risk infrastructure and emergency response • Create a geographical information system (GIS) database of slope failures • Create emergency response contracts with construction firms to augment state resources if extreme weather strikes • Install more traffic cameras along arterials • Preposition heavy-duty tow trucks for winter storms • Ensure traffic camera power supply continuity • Explore use of satellite road surface temperature data from National Oceanic and Atmospheric Administration • Convey detour route information to drivers during incidents • Complete update of geotech manual • Train maintenance crews on basics of slope engineering • Enhance marketing of 511 service, especially to trucks • Review equipment needs related to extreme weather response • Enhance brine use • Review salt supply policies in case of back-to-back storms • Coordinate plowing and road closure decisions with neighboring states • Implement incident severity detection • Create checklist for on-scene incident response managers • Develop integrated tracking of major incidents between Statewide Operations Centers (SOCs) and Traffic Operations Centers (TOCs) • Integrate real-time citizen road condition reporting with operations decision making • Integrate real-time video feeds from state vehicles into operations decisions • Update contra-flow plans ***Preventive Actions*** • Change all signal wires to mast arms • Pilot snow hoods on LED stoplights • Enhance the culvert and stormwater maintenance program and provide additional funding • Work with Maryland Department of the Environment to streamline environmental regulations relating to culvert cleaning • Coordinate with metropolitan planning organizations on climate adaptation initiatives • Install monitoring devices on vulnerable slopes • Review erosion and sedimentation standards • Increase tree-trimming activities to meet needs ***Administrative Actions*** • Provide overtime instead of comp time for severe weather response • Clarify departmental responsibility for bridge approaches

Table I.4. (Continued).

Goal	Actions
Develop a stronger understanding of the long-term implications of a changing climate on the state's highway network	• Identify sources of climate projections for key infrastructure design parameters through the year 2100 • Designate official State Highway Administration/Maryland Transportation Authority climate projections (climate models, downscaling technique, and emissions scenarios to use) • Identify the key climate threats to the transportation system through the year 2100 and their expected onset dates • Identify critical thresholds where asset functionality and safety will be jeopardized and enter into asset management system • Conduct high-level system-wide risk analysis of the climate threats to SHA assets; begin with one county pilot analysis • Conduct detailed asset-specific vulnerability analyses for the most critical and unsafe high-risk assets • Share risk analysis findings with the general public • Develop denser network of stream gauges • Integrate maintenance records and the asset management system • Create a lessons-learned library for responding to climate change and extreme weather • Clarify what perpetual responsibility for environmental mitigation measures means vis-à-vis climate change
Develop long-term policy strategies for adapting existing infrastructure to climate changes as the need arises	• Create an internal climate change adaptation task force • Develop a menu of possible adaptation solutions for common climate threats • Identify funding sources for the standard adaptation solutions • In consultation with the general public, set trigger thresholds for each asset that will initiate adaptation actions • Using climate projections, forecast when the trigger thresholds are to be crossed for planning and budgeting purposes • Develop and implement a monitoring system to determine when trigger thresholds are surpassed • Enhance coordination on land use decisions that affect state roads • Incorporate adaptation language in review of local comprehensive plans and site plans • Link streamflow monitoring with stormwater management policies
Consider adaptations in new projects to increase their resiliency to future climate impacts	• Incorporate climate adaptation needs into system planning and capital program development • Incorporate climate change adaptation into the project development process • Develop a transparent benefit–cost analysis methodology for comparing various adaptation options (including business as usual) • Flag all projects lying in potential sea-level rise inundation areas • Incorporate adaptations into new project siting and designs when necessary

Source: Maryland State Highway Administration (2012).

- **Focus of the action**, which describes what the action is meant to address.
- **Co-benefits** that note any additional benefits to the action item beyond the adaptation benefits, including
  - System reliability,
  - Safety,
  - Morale, and
  - Efficiency.
- **Cost avoided** (benefit), which provides a rough dollar-value estimate of the average annual costs to be saved by implementing the adaptation action.
- **Cost**, which provides a rough dollar-value estimate of the costs of implementing the action item statewide.
- **Timeframe** to initiate the action, including
  - 2012–2013,
  - 2014–2015, and
  - 2016 or beyond.

- Agency office responsible for implementation, which includes whether in a lead or support role. (Note: Sixteen different agency offices were given some level of responsibility in implementing the policy).

Each agency should assess its own portfolio of potential actions in light of the types of climate stresses that will be faced by the transportation system. This assessment will likely result in similar types of actions (e.g., design of bridges in higher-than-normal flood zones) and could also result in actions specific to certain circumstances (e.g., protection against storm surge on top of expected sea-level rise). The actions that are included in the portfolio would also be tempered by the results of Step 2 of the diagnostic framework, which identified the types of assets that will receive attention by the agency.

Summary

Table I.5 summarizes the expected impacts on the transportation system from changes in temperature, precipitation, sea-level rise, and hurricanes. The potential impacts of changes in climate on the nation's road system are wide ranging, which underscores the importance of considering climate change in all phases of transportation decision making where vulnerability is expected (National Research Council 1987). A long-range perspective on possible threats to infrastructure

Table I.5. Summary of climate change impacts on the highway system.

Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
	Temperature	
Change in extreme maximum temperature	• Premature deterioration of infrastructure. • Damage to roads from buckling and rutting. • Bridges subject to extra stresses through thermal expansion and increased movement.	• Safety concerns for highway workers limiting construction activities. • Thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs. • Vehicle overheating and increased risk of tire blowouts. • Rising transportation costs (increase need for refrigeration). • Materials and load restrictions can limit transportation operations. • Closure of roads because of increased wildfires.
Change in range of maximum and minimum temperature	• Shorter snow and ice season. • Reduced frost heave and road damage. • Later freeze and earlier thaw of structures because of shorter freeze-season lengths • Increased freeze–thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces. • Increased slope instability, landslides, and shoreline erosion from permafrost thawing leads to damaging roads and bridges due to foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost). • Hotter summers in Alaska lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.	• Decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, and result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles. • Longer road construction season in colder locations. • Vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons). • Roadways built on permafrost likely to be damaged due to lateral spreading and settlement of road embankments. • Shorter season for ice roads.

Table I.5. (Continued).

Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
Precipitation		
Greater changes in precipitation levels	• If more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction. • Increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration). • Less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode. • Road embankments could be at risk of subsidence/heave. • Subsurface soils may shrink because of drought.	• Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents). • Roadways and underground tunnels could close due to flooding and mudslides in areas deforested by wildfires. • Increased wildfires during droughts could threaten roads directly or cause road closures due to fire threat or reduced visibility. • Clay subsurfaces for pavement could expand or contract in prolonged precipitation or drought, causing pavement heave or cracking.
Increased intense precipitation, other change in storm intensity (except hurricanes)	• Heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting), which could lead to permanent road closures. • Heavy precipitation and increased runoff can cause damage to tunnels, culverts, roads in or near flood zones, and coastal highways. • Bridges are more prone to extreme wind events and scouring from higher stream runoff. • Bridges, signs, overhead cables, and tall structures could be at risk from increased wind speeds.	• The number of road closures due to flooding and washouts will likely rise. • Erosion will occur at road construction project sites as heavy rain events take place more frequently. • Road construction activities could be disrupted. • Increases in weather-related highway accidents, delays, and traffic disruptions are likely. • Increases in landslides, closures or major disruptions of roads, emergency evacuations, and travel delays are likely. • Increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/maneuverability, lane obstruction (debris), and treatment chemical dispersion. • Lightning/electrical disturbance could disrupt transportation electronic infrastructure and signaling, pose risk to personnel, and delay maintenance activity.
Sea Level		
Sea-level rise	• Erosion of coastal road base and undermining of bridge supports due to higher sea levels and storm surges. • Temporary and permanent flooding of roads and tunnels due to rising sea levels. • Encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events). • Further coastal erosion due to the loss of coastal wetlands and barrier islands removing natural protection from wave action.	• Coastal road flooding and damage resulting from sea-level rise and storm surge. • Increased exposure to storm surges. • More frequent and severe flooding of underground tunnels and other low-lying infrastructure.
Hurricanes		
Increased hurricane intensity	• Increased infrastructure damage and failure (highway and bridge decks being displaced).	• More frequent flooding of coastal roads. • More transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods). • More coastal evacuations.

in the future and the risks to this infrastructure should be considered in today's decision making. This long-range perspective needs to be balanced with monitoring for near-term changes that may require more immediate adjustments.

In addition to the direct effects on transportation infrastructure and services, climate change will likely cause changes in the environmental, demographic, and economic contexts within which transportation agencies conduct their work. In the long run, these broader changes may have very significant secondary impacts on the transportation sector that will need to be examined as part of the planning process.

The IPCC's report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* suggests that approaches to adaptation and disaster risk management can be complementary and effectively combined (IPCC 2012). The report discusses many options currently available to help improve responses to extreme climate events and disasters. The IPCC report recommends that an iterative process involving monitoring, research, evaluation, learning, and innovation can reduce the risk from climate extremes and long-term climate change.

An important conclusion from this examination of potential impacts of climate change on the nation's road system is that not only could such change affect the physical and operational characteristics of facilities and systems where vulnerability exists, but so too will the consideration of such change influence the processes and procedures followed by transportation officials in providing this transportation system.

CHAPTER 5

Vulnerability Assessments and Risk Appraisals for Climate Adaptation

Although each step in the adaptation planning process is important from the perspective of conducting an adaptation study, one step in particular is critical to the overall success of the process—the identification of the risk associated with system or facility disruption due to long-term changes in the climate or due to extreme weather events. Given that the legacy of facility location decisions can last far beyond the useful life of a project (that is, there is a good chance a facility will be rebuilt or expanded), infrastructure decisions can result in facilities that will be subject to climatic stressors for many decades, if not over a century for some facilities like bridges. As shown in Figure I.2, risk appraisals are typically conducted subsequent to the asset vulnerability assessment for the purpose of better understanding the nature of potential climate impacts on infrastructure. Ideally, risk appraisal leverages information from the vulnerability assessment, especially details on potential asset exposure, sensitivity, and adaptive capacity to climate stressors.

What Is the Difference between Vulnerability and Risk?

An asset is vulnerable to climatic conditions if these conditions (such as intense precipitation and extreme temperatures) and their aftermath (e.g., a flood exceeding certain stages and consecutive days of higher than 100°F temperatures) result in asset failure or sufficient damage to reduce asset functionality. The vulnerability can thus be measured as the probability that the asset will fail given climate stressors (e.g., "there is a 90 percent chance the bridge in its current condition will fail with a 500-year flood"). Vulnerability primarily focuses on the condition of the asset.

Climate-related risk is more broadly defined; it relates to not only the failure of the asset but also to the consequences or magnitudes of costs associated with that failure (Willows and Connell 2003). In this case, a consequence might be the direct replacement costs of the asset, direct and indirect costs to asset users, and, even more broadly, the economic costs to society given the disruption to transportation caused by failure of the asset or even temporary loss of the asset's services (e.g., a road is unusable when it is under water). The importance of broader economic costs to the risk analysis should not be underestimated. For example, if a bridge is located on the only major road serving a rural community and there is a possibility that the bridge could be washed out with major storms, the measure of consequence should include the economic impacts of isolating that community for some period of time while the bridge is being replaced.

Putting it all together, the complete risk equation is thus:

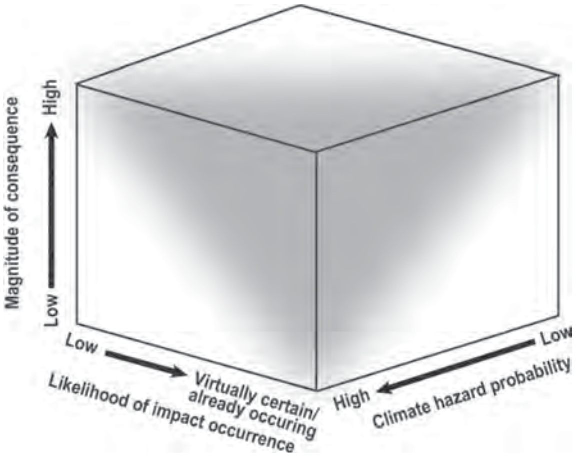
$$\begin{aligned} Risk = {} & Probability\ of\ Climate\ Event\ Occurrence \times Probability\ of\ Asset\ Failure \\ & \times Consequence\ or\ Costs \end{aligned}$$

The risk equation shows that low-probability climate events (e.g., a Category 5 hurricane hitting the community) with high probabilities of asset failure and high consequence costs could still have high risk scores. Likewise, events with lower consequence costs but greater probability of occurrence or failure could lead to similarly high risk scores.

Most transportation-related climate change risk appraisals performed to date have embraced this general risk conceptualization involving likelihoods of climate events occurring, probability of asset failure, and magnitude of the consequence. For example, the FHWA Conceptual Model (FHWA 2012d), ICLEI's "Preparing for Climate Change: A Guide for Local, Regional, and State Governments" (Center for Science in the Earth System and King County (WA) 2007), the U.K. Climate Impact Program on Climate Change Risk (U.K. Climate Impacts Programme 2003), and the New York City Panel on Climate Change's "Climate Change Adaptation in New York City" (New York City Panel on Climate Change 2010) have each adopted the multifactor approach to risk.

Although many risk frameworks consider "probability of impact" as a composite factor, others—such as the NYC Panel on Climate Change's three-dimensional climate change assessment matrix (shown in Figure I.7)—look at the components of probability individually. For purposes of this guide, two approaches to risk appraisal will be presented; the approach chosen will depend on the reader's access to, or willingness to develop, numerical probability information. It is worth noting that very few of the risk appraisals in the transportation sector conducted to date have actually assigned numerical probabilities to these risk factors although research is moving in this direction.

To determine vulnerability as part of an adaptation assessment, which assets, asset types, or locations are to be targeted must be determined first—simply because a transportation agency will not have enough resources to climate-proof all of its assets. As shown in the diagnostic framework (Figure I.2), several steps precede the vulnerability and risk appraisal steps. Understanding the likely climate stressors is clearly important for understanding potential threats. However, as shown in the diagnostic framework it is also important to define the focus or purpose of the adaptation assessment process. Is the agency going to focus only on assets that are considered most important from an interstate commerce perspective? Or is it going to identify the most vulnerable assets no matter where in the network and invest



Source: New York City Panel on Climate Change (2010).

Figure I.7. Three-dimensional climate change assessment matrix.

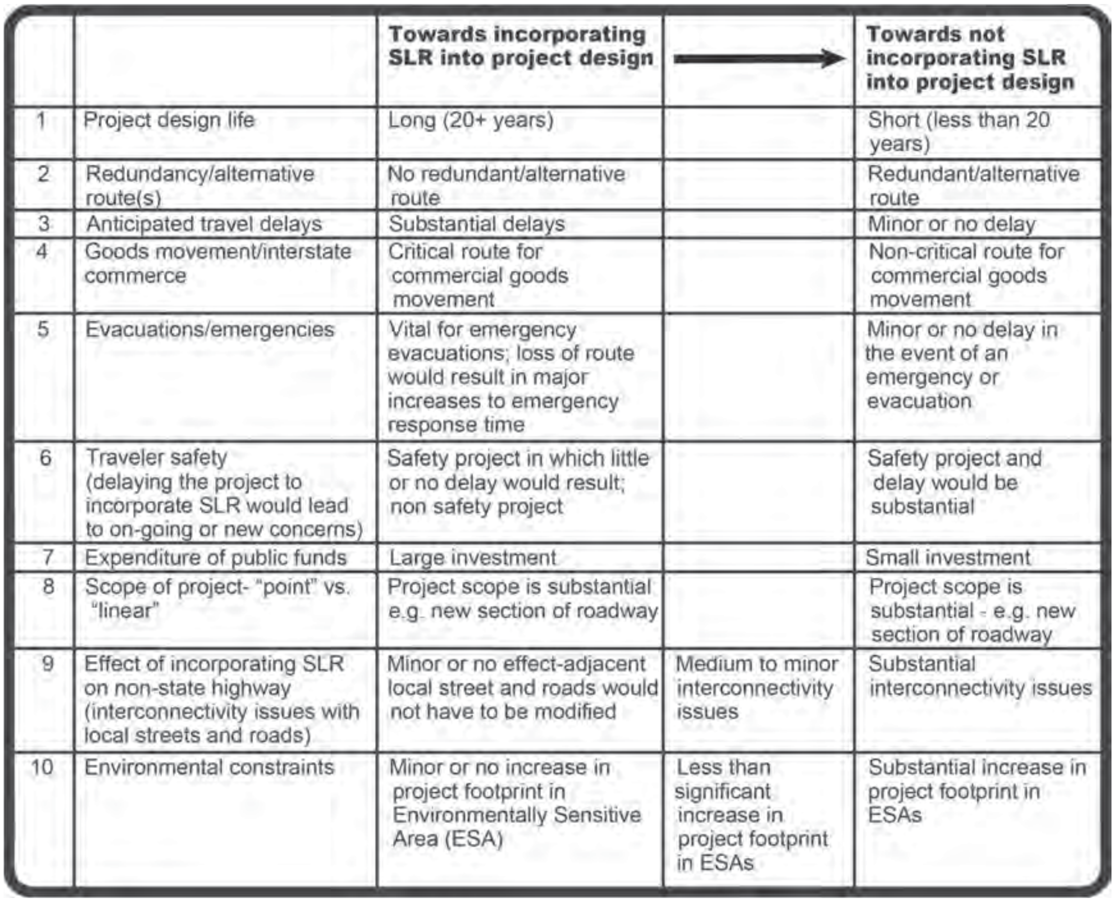
in asset protection? Or is the agency going to fix the weather-related problems the highway network is currently facing on the assumption that such problems will only be exacerbated in the future?

An example from California illustrates how a state can establish policies or guidelines on when adaptation action will be taken. In response to a gubernatorial executive order, the California Department of Transportation (Caltrans) developed guidelines for considering SLR in project planning documents (California Department of Transportation 2011). As noted in the guidance, not only will enhancing the design features of structures likely be a consideration, but so too will be increasing costs for permit fees and mitigation. A three-part screening process was recommended, in essence answering the following questions:

1. Is the project located on the coast or in an area vulnerable to SLR?
2. Can the project be impacted by the stated SLR?
3. Is the design life of the project beyond year 2030?

If it is determined that SLR needs to be considered as part of the design, the project initiation document must provide a detailed discussion of potential impacts and how they might affect the design. Table I.6 shows the factors used to decide whether to incorporate SLR. In other words, for those assets that have a short project design life, where redundant or alternative routes exist, and anticipated delays will be minor, Caltrans will tend not to incorporate SLR adaptation actions into project design.

Table I.6. Caltrans' considerations in incorporating sea-level rise adaptation into design.



		Towards incorporating SLR into project design	→	**Towards not incorporating SLR into project design**
1	Project design life	Long (20+ years)		Short (less than 20 years)
2	Redundancy/alternative route(s)	No redundant/alternative route		Redundant/alternative route
3	Anticipated travel delays	Substantial delays		Minor or no delay
4	Goods movement/interstate commerce	Critical route for commercial goods movement		Non-critical route for commercial goods movement
5	Evacuations/emergencies	Vital for emergency evacuations; loss of route would result in major increases to emergency response time		Minor or no delay in the event of an emergency or evacuation
6	Traveler safety (delaying the project to incorporate SLR would lead to on-going or new concerns)	Safety project in which little or no delay would result; non safety project		Safety project and delay would be substantial
7	Expenditure of public funds	Large investment		Small investment
8	Scope of project- "point" vs. "linear"	Project scope is substantial e.g. new section of roadway		Project scope is substantial - e.g. new section of roadway
9	Effect of incorporating SLR on non-state highway (interconnectivity issues with local streets and roads)	Minor or no effect-adjacent local street and roads would not have to be modified	Medium to minor interconnectivity issues	Substantial interconnectivity issues
10	Environmental constraints	Minor or no increase in project footprint in Environmentally Sensitive Area (ESA)	Less than significant increase in project footprint in ESAs	Substantial increase in project footprint in ESAs

Source: California Department of Transportation (2011).

Why Consider Climate-Related Risk?

Risk assessments are performed to provide a platform for climate change adaptation decision making and planning to ensure the future resiliency of transportation infrastructure. Today's infrastructure comprises the greater portion of tomorrow's infrastructure in many jurisdictions. Risk assessments provide a basis for the cost-effective protection of long-term infrastructure investments, as demonstrated by the climate risk adjusted benefit–cost methodology in Chapter 6. Risk scoring can support the choice and timing of adaptation investments, helping distinguish between the merits of incremental improvements versus (or in concert with) major, singular investments and providing guidance as to when implementation should occur. An understanding of risk is also crucial to asset management plans and protocols, which could include proactive treatments to enhance asset resiliency or minimal intervention in anticipation of replacement, major reconstruction, or even abandonment. Particularly for assets that are expected to last beyond 2050, or even 2100, it is important to mitigate the risks of failure, deterioration, or frequent disruption due to climate hazards. Risk assessments may also be employed to identify potential infrastructure needed to effectively respond to climate hazards by instituting redundancy for potentially affected critical roadway segments, bridges, or culverts.

From a practical perspective, knowing whether the location and/or design of the facility presents a high level of risk to disruption due to future climate change is an important part of the design decision. For existing infrastructure, identifying high-risk assets or locations provides decision makers with some sense of whether additional funds should be spent to lower future climate change–related risk when reconstruction or rehabilitation occurs. This identification could include conducting an engineering assessment of critical assets that might be vulnerable to climate stressors. This approach, in essence, "piggybacks" adaptation strategies on top of other program functions (e.g., maintenance, rehabilitation, reconstruction, etc.).

What If Probabilities Are Not Available?

Although some climate change event is likely to occur sometime and somewhere, the date of onset and the location and/or the frequency of occurrence are uncertain, especially in the distant future when there is much uncertainty about GHG emissions trajectories and how much climate will change as the result of those different trajectories. So, determining the likelihood of a climate event occurring is challenging. This approach is further complicated by the fact that the SRES emissions scenarios (Nakicenovic et al. 2000) and general circulation models do not provide such probabilities; the IPCC's official position is that each emissions scenario has an equal probability of occurrence.

Due to the difficulties in identifying probabilities, climate risk is often characterized very broadly and qualitatively (e.g., high, medium or low, or on a scale from 1 to 10). Obtaining a plausible characterization of likelihood—one that balances accuracy with precision—is a challenge inherent in climate risk assessment.

Several recent studies have used alternative approaches to handling the uncertainty in climate events occurring, which provide possible options for considering the likelihood of climate events occurring:

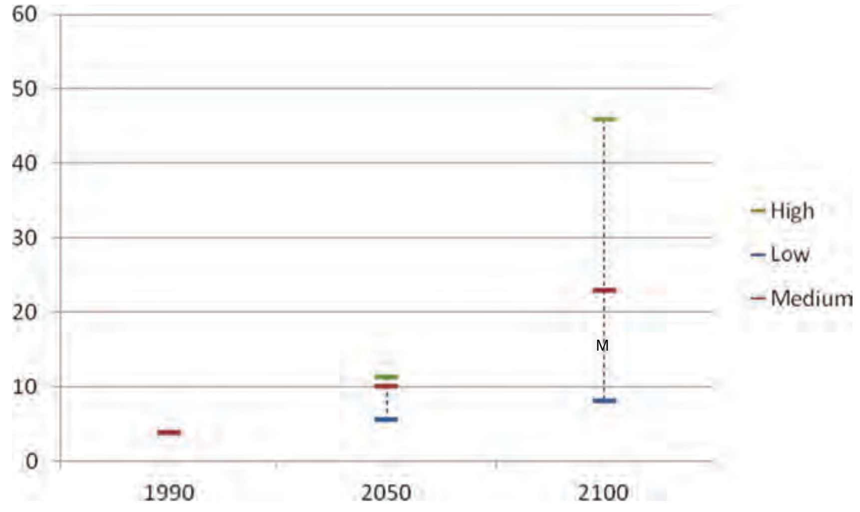
- **Establish thresholds for climate stressors:** This approach defines thresholds for planning and design and does not worry if they will be reached. For example, common SLR thresholds were established for planning purposes in California (Sea-Level Rise Task Force of the Coastal and Ocean Resources Working Group for the Climate Action Team 2010) and used by the Bay

Area's Metropolitan Transportation Commission in its "Adapting to Rising Tides" report (Metropolitan Transportation Commission et al. 2011). Another way of looking at this is that since the climate will continue to warm indefinitely until CO_2 levels are stabilized, a safe assumption is that any threshold will eventually be reached. WSDOT's pilot project for the FHWA's conceptual adaptation model chose to eliminate timeframe when conducting scenario analysis, in other words the researchers assumed the climate stressor was going to happen and did not worry about when (WSDOT 2012).

- **Given climate model results, adopt one of the forecasts as the "design" conditions:** Due to limited resources, the North Jersey Transportation Planning Authority (NJTPA)/New Jersey DOT FHWA pilot project adopted a single, mid-range value for its transportation asset risk analysis. The project included the generation of high, medium, and low stressor values to bracket the range of plausible climate outcomes, which it suggested pairing with assets of high, medium, and low criticality (see Figure I.8) (NJTPA 2011). Highly critical assets—those essential to system functionality, for example—would be assessed for potential vulnerability and thus risk using the highest stressor values, assets of medium criticality with medium stressor values, and so on. This model of risk management reflects a Dutch-style approach to planning amid uncertainty, where assets that absolutely cannot fail (such as dykes and levees) are designed to withstand the most extreme events (such as the one in 10,000 years storm event).

With respect to the probability of an asset's failure (e.g., destruction, deterioration, or disruption) when subjected to a particular climate stress, an asset's design and material specifications, along with its anticipated condition in the future analysis year, may offer clues as to its expected resiliency—but assigning a reasonably specific failure probability is very challenging. This could be facilitated by the identification of asset vulnerabilities, usually determined prior to the risk assessment phase. Although vulnerability assessment is often regarded as a separate step, prior vulnerability assessment activities may be leveraged to develop information for risk assessment. The determination of likelihood of asset failure should rely on formal engineering assessments of asset condition and failure modes, or engineering judgment on what will likely occur given different levels of stress.

The estimation of the magnitude of consequence answers the question, what is the consequence of a damaged, deteriorated, or disrupted asset to the transportation system (and its users) and to communities that possibly rely on that asset or are in other ways affected by a



Source: NJTPA (2011).

Figure I.8. Climate stressor brackets for average annual number of days equal to or exceeding 95°F in Atlantic City, NJ, 1990–2100.

failed asset? Part of answering this question is understanding how long the consequences might last, e.g., years, weeks, or hours or until capacity is regained through restoration, utilization of redundant assets, or changing mode of travel. The consequences themselves are multidimensional, potentially extending well beyond dollars lost or trips disrupted. The importance of different consequences will differ by agency, but DOTs may wish to include such factors as the following:

- **Direct agency costs**—incorporates the direct costs of restoring service—for example, bridge repairs required to regain functionality—with the potential for direct revenue losses, such as tolls.
- **Direct user costs**—considers the costs to the users of a facility whose travel is now disrupted and who now might incur extra costs due to asset failure (e.g., extra time to detour around a disruption).
- **Indirect costs**—includes broader economic repercussions, if there is a basis for estimating them (for example, lost economic activity in surrounding communities due to loss of access).
- **Safety**—includes health and life safety impacts to drivers, pedestrians, or others.
- **Environment**—includes impacts to natural systems such as wetlands that provide important functions in the ecological community surrounding transportation facilities.
- **Reputation**—involves public confidence in an agency's ability to deal with emergency situations; not measured in dollar terms but increasing public confidence is an important consequence to agency officials.

Together, "probability of climate event occurrence," "probability of failure of asset" and "magnitude of consequence"—no matter how they are measured or how many intermediate steps they entail—yield a measure of integrated risk. With a completed catalog of integrated risks, transportation agencies can embark on climate change adaptation planning endeavors with a sense of their priorities.

How Can the Results of Risk Assessment Be Portrayed without Probabilities?

Several methods have been used to conduct a risk assessment without the use of probabilities; they fall into three major categories: risk assessment matrix, numerical scoring, and probability ranges.

Risk Assessment Matrix

Figure I.9 is offered by the FHWA as one way of including both the likelihood of a climate event occurring and the potential level of disruption given that the event occurs (FHWA 2012a). WSDOT used this approach in identifying which of its assets were at highest risk for different types of climate stressors. Figure I.10 shows how the different WSDOT assets could be rated with respect to risk (WSDOT 2011).

Numerical Scoring

Another approach to risk assessment is to establish criteria for the component parts of risk and then rate each asset from the perspective of potential level of effect. For example, the U.K. Highways Agency developed a risk-based adaptation process that focused on four risk criteria: uncertainty, rate of climate change, extent of disruption, and severity of disruption

Caltrans' Risk-Based Decision Making for Bridge Seismic Retrofit

Caltrans' decision-making process on whether a bridge should be considered for retrofit is based on a multiattribute prioritization process. The screening steps are as follows:

1. Development of a computerized prioritization algorithm to evaluate the various attributes of each bridge and to assign a quantified ranking for retrofit. The algorithm includes classification and scoring of the various bridges on the basis of three major evaluation categories:
   a. Vulnerability of the structure
   b. Seismic hazard
   c. Potential impact on the community

Each of these categories is composed of a number of sub-elements (presented in summary table).

2. Initial screening of the state, county, and city bridges to determine their seismic vulnerability (approximately 7,000 state bridges and 4,000 county and city bridges were identified as potentially hazardous bridges).
3. Detailed plan review of the 11,000 potentially hazardous bridges.
4. Detailed seismic evaluation of the remaining bridges in order of priority to identify structural deficiencies for retrofit.
5. Design and preparation of necessary construction documents to implement the retrofit. Unlike prior retrofit programs, this program systematically addressed deficiencies in all the structural components of each bridge.

Development of the risk screening and prioritization algorithm enabled Caltrans engineering staff to screen and then prioritize the retrofitting of a large volume of bridges in California. To more efficiently assist the prioritization of single-column bridges, a level-one risk assessment was utilized. The difference between a conventional and level-one risk analysis is that professional judgment is used to augment and/or take the place of the massive data-supported statistical distributions utilized in the conventional approach (Roberts and Maroney 2000).

The basic formula for prioritization is summarized as follows (National Research Council 1994):

Prioritization = (Activity)(Hazard)[(0.60)(Impact) + (0.40)(Vulnerability)], where

Activity = Global Utility Function Value
Hazard = Σ(Attribute Weight)(Global Utility Function Value)
Impact = Σ(Attribute Weight)(Global Utility Function Value)
Vulnerability = Σ(Attribute Weight)(Global Utility Function Value)

Caltrans made further adjustments based on several considerations including the following:

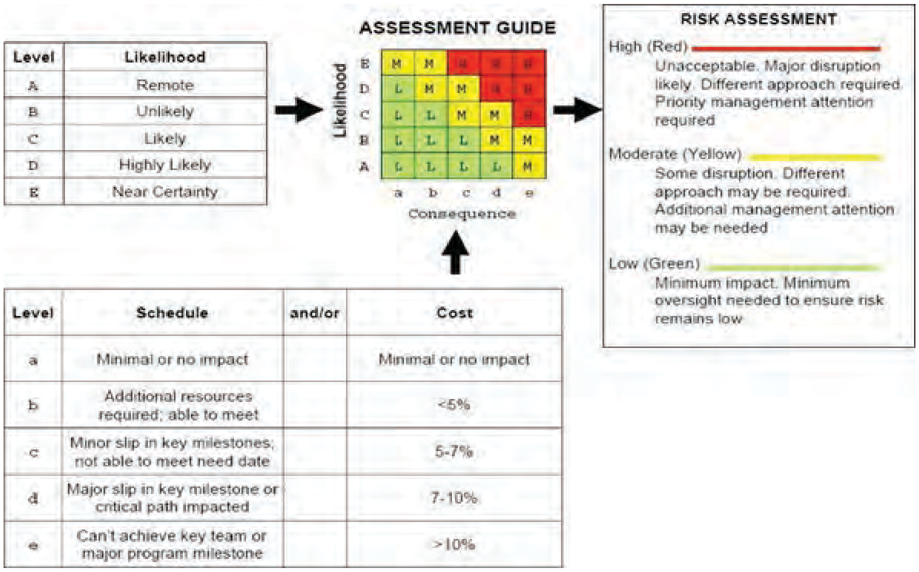
- Routes and regions in common-sense bridge groups rather than single bridges
- Special cases, such as bridges supporting critical utilities
- Community leader and local concerns

(continued on next page)

Caltrans' Risk-Based Decision Making for Bridge Seismic Retrofit *(Continued)*

Summary of multiattribute decision procedure elements showing weighting percentages applied to each attribute.

Attributes	Weight
Hazard Criteria	
Soil conditions	33%
Peak rock acceleration	38%
Seismic duration	29%
Impact Criteria	
Average daily traffic on structure	28%
Average daily traffic under/over structure	12%
Detour length	14%
Leased air space (residential, office)	15%
Leased air space (parking, storage)	7%
Route type on bridge	7%
Critical utility	10%
Facility crossed	7%
Vulnerability Criteria	
Year designed (construction)	25%
Hinges (drop type failure)	16.5%
Outriggers, shared column	22%
Bent redundancy	16.5%
Skew	12%
Abutment type	8%



Level	Likelihood
A	Remote
B	Unlikely
C	Likely
D	Highly Likely
E	Near Certainty

ASSESSMENT GUIDE

Likelihood	a	b	c	d	e
E	M	M	H	H	H
D	L	M	M	H	H
C	L	L	M	M	H
B	L	L	L	M	M
A	L	L	L	L	M

Consequence

RISK ASSESSMENT

High (Red)
Unacceptable. Major disruption likely. Different approach required. Priority management attention required

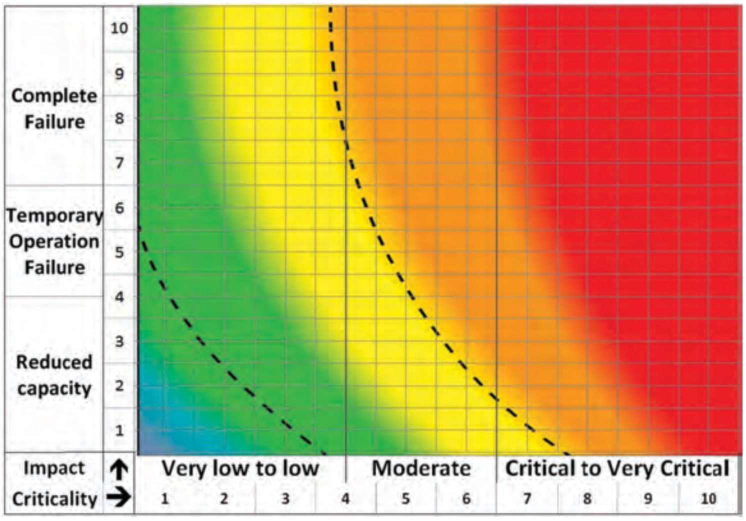
Moderate (Yellow)
Some disruption. Different approach may be required. Additional management attention may be needed

Low (Green)
Minimum impact. Minimum oversight needed to ensure risk remains low

Level	Schedule	and/or	Cost
a	Minimal or no impact		Minimal or no impact
b	Additional resources required; able to meet		<5%
c	Minor slip in key milestones; not able to meet need date		5-7%
d	Major slip in key milestone or critical path impacted		7-10%
e	Can't achieve key team or major program milestone		>10%

Source: FHWA (2012a).

Figure I.9. An approach for considering risk in decision making.



Source: WSDOT (2011).

Figure I.10. WSDOT's assessment approach for identifying assets at risk.

(Highways Agency and Parsons Brinckerhoff 2008). Each of these criteria was ranked on the basis of a high (three points), medium (two points) or low (one point) score. For example, for extent of disruption, three points were assigned if the disruption was expected to affect 80 percent of the network or any strategic route in the network; two points for 20 to 80 percent disruption; and one point for less than 20 percent disruption. Similarly, for the severity of disruption, three points were assigned if the duration was greater than 1 week; two points if it was to last 1 day to 1 week; and one point if it was less than 1 day. Based on the risk appraisal and a combination of the different risk factors, the concerns in the following list were identified as being potentially highly disruptive and time critical with high levels of confidence in the appraisal. The tiers reflect the level of importance (and thus attention of agency officials) associated with each concern. Thus, pavement skid resistance (Tier 1) was considered to be an issue that the agency needed to work on more than high levels of wind (Tier 2).

- Tier 1
  - Pavement skid resistance
  - Identifying best ways of investing resources/investment appraisals
- Tier 2
  - Wind actions (loads) applied to superstructures
  - Designs for increased scour for foundations
  - Pavement material integrity
  - Strategic geographic importance of a region
  - Network resilience
  - Budgeting
  - Staffing
- Tier 3
  - Pavement materials specification and construction details
  - Design of pavement foundations
  - Design of bearings and expansion joints
  - Surface water drainage

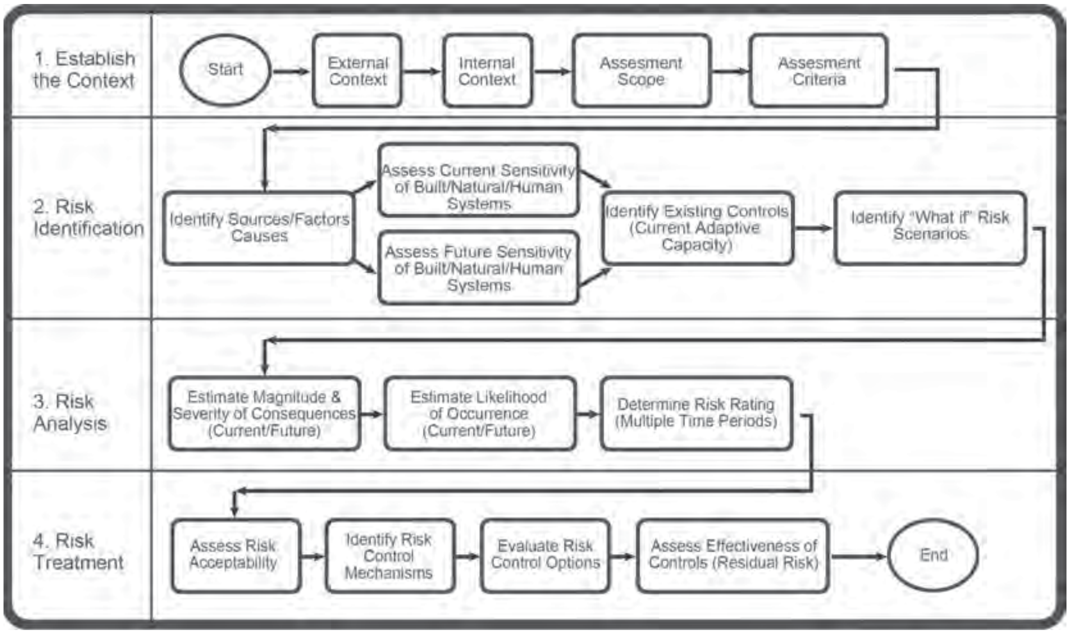
- Attenuation and outfalls
- Pavement maintenance
- Flooding

An adaptation work program was adopted that outlined specific tasks for each of the agency's units.

Probability Ranges

If an exact probability for an event occurring cannot be determined, this approach assigns probability ranges and links them to qualitative descriptors. The studies that have used this approach in essence state that although it is difficult to estimate with certainty that a certain event will occur, say, with a 60 percent probability, the probability of the event occurring can be estimated with some level of confidence to fall within a 55 to 90 percent probability range. This range could then be labeled a "highly likely" probability.

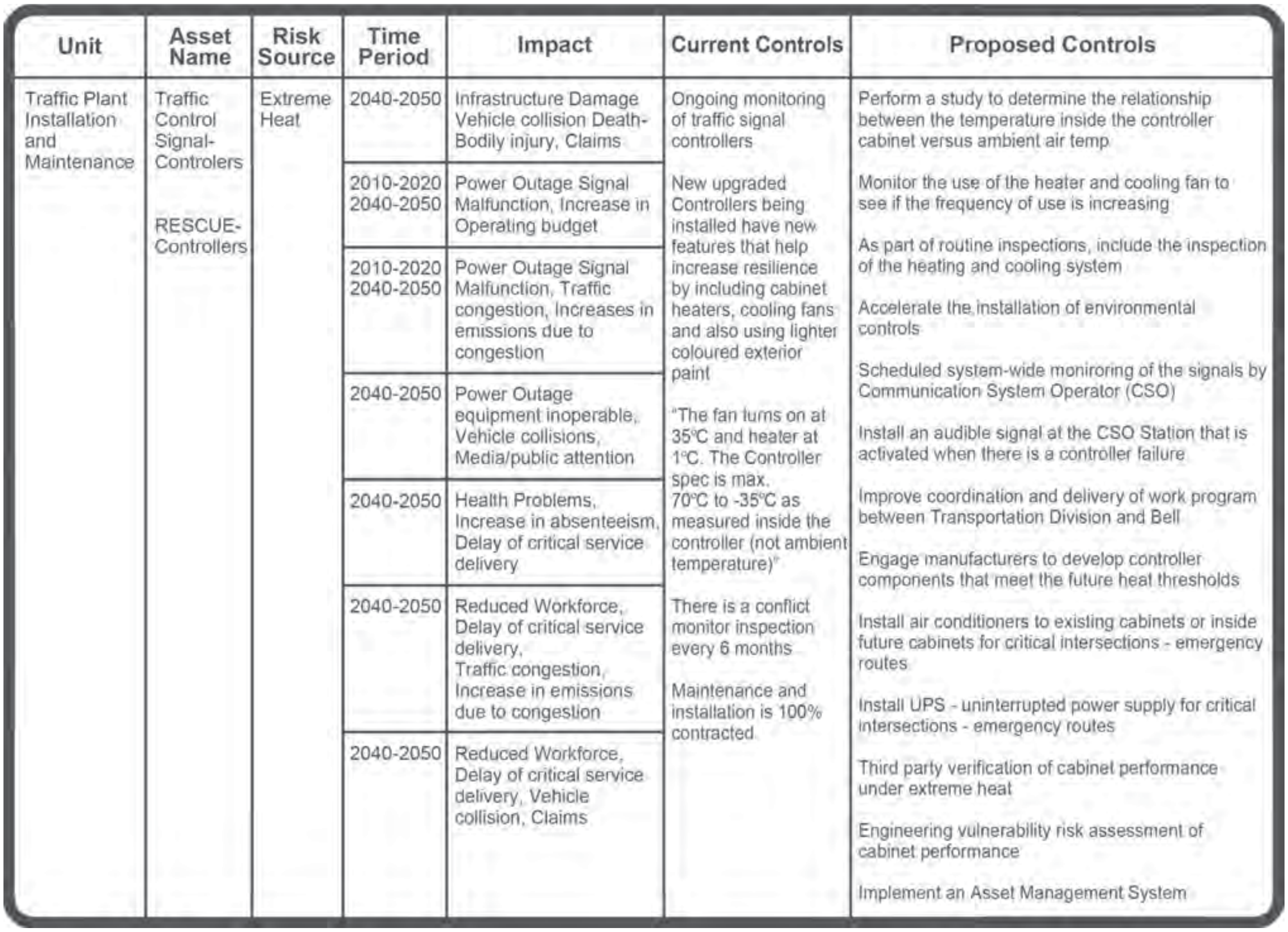
For example, the City of Toronto has developed an environmental risk assessment process and tool (see Figure I.11) that "assesses general environmental risks, such as: regulatory requirements, impacts to the environment by City operations, as well as the effects of climate change on the delivery of services, management of infrastructure and protection of the natural environment" (City of Toronto 2011). The tool was developed based on the international risk standard ISO 31000 and took into account elements of ISO 14001, the international environmental management system standard, as well as many core principles from the field of environmental auditing. In essence, the tool is software that allows users to identify likely climate change impacts and the risks to vulnerable infrastructure or services. The likelihood of a climate event occurring was characterized similar to what is shown in Figures I.9 and I.10 along with probability ranges, that is, "almost certain" (90 to 100 percent probability), "very likely" (55 to 90 percent), "likely" (30 to 55 percent), "unlikely" (5 to 30 percent), and "rare" (0 to 5 percent).



Source: City of Toronto (2011).

Figure I.11. Adaptation planning process in Toronto.

Table I.7. Example assessment of Toronto transportation assets in context of extreme heat.



Unit	Asset Name	Risk Source	Time Period	Impact	Current Controls	Proposed Controls
Traffic Plant Installation and Maintenance	Traffic Control Signal-Controlers RESCUE-Controllers	Extreme Heat	2040-2050	Infrastructure Damage Vehicle collision Death-Bodily injury, Claims	Ongoing monitoring of traffic signal controllers New upgraded Controllers being installed have new features that help increase resilience by including cabinet heaters, cooling fans and also using lighter coloured exterior paint "The fan turns on at 35°C and heater at 1°C. The Controller spec is max. 70°C to -35°C as measured inside the controller (not ambient temperature)" There is a conflict monitor inspection every 6 months Maintenance and installation is 100% contracted	Perform a study to determine the relationship between the temperature inside the controller cabinet versus ambient air temp Monitor the use of the heater and cooling fan to see if the frequency of use is increasing As part of routine inspections, include the inspection of the heating and cooling system Accelerate the installation of environmental controls Scheduled system-wide moniroring of the signals by Communication System Operator (CSO) Install an audible signal at the CSO Station that is activated when there is a controller failure Improve coordination and delivery of work program between Transportation Division and Bell Engage manufacturers to develop controller components that meet the future heat thresholds Install air conditioners to existing cabinets or inside future cabinets for critical intersections - emergency routes Install UPS - uninterrupted power supply for critical intersections - emergency routes Third party verification of cabinet performance under extreme heat Engineering vulnerability risk assessment of cabinet performance Implement an Asset Management System
			2010-2020 2040-2050	Power Outage Signal Malfunction, Increase in Operating budget		
			2010-2020 2040-2050	Power Outage Signal Malfunction, Traffic congestion, Increases in emissions due to congestion		
			2040-2050	Power Outage equipment inoperable, Vehicle collisions, Media/public attention		
			2040-2050	Health Problems, Increase in absenteeism, Delay of critical service delivery		
			2040-2050	Reduced Workforce, Delay of critical service delivery, Traffic congestion, Increase in emissions due to congestion		
			2040-2050	Reduced Workforce, Delay of critical service delivery, Vehicle collision, Claims		

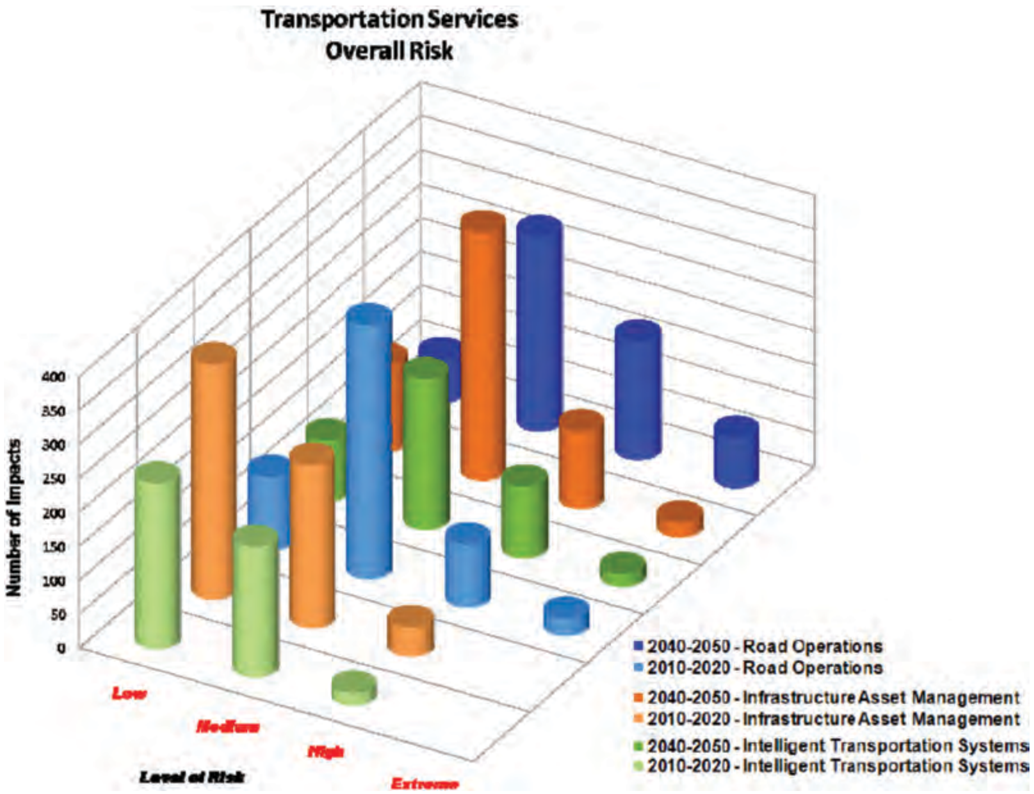
Source: City of Toronto (2011).

The results of the tool application are shown in Table I.7 and Figure I.12. As shown in Figure I.2, Toronto has used the tool to determine the overall risk for the key assets that it is responsible for. These assets include road operations, road assets, and intelligent transportation systems. The types of actions that have been taken in response to this process include increasing the size of storm sewers and culverts for new designs to handle greater volumes of runoff, increasing the inspection and maintenance of culverts on a regular basis and especially after storm events, installing permeable surfaces to reduce runoff from heavy rainfall, and landscaping with drought-resistant plants.

What If Probabilities Are Available or Could Be Developed?

Where could the probabilities of climate events occurring and asset failures happening come from? There are several possible sources for such probabilities (and with continuing advancements in climate science more sources could become available in the future):

- **For climate events**
  - ***Expert opinion:*** Climate science is continually adding to our knowledge about climate and weather events. Experts in such events could provide their best estimate of the likelihood of certain climate stressors occurring over some time period.



Source: City of Toronto (2011).

Figure I.12. Overall transportation system risk assessment to climate change, Toronto.

- ***Scientific studies:*** Some changes in climate stressors are more firmly grounded in scientific studies than others. For example, as noted in Chapter 3, predictions in changes in temperature have higher levels of confidence associated with them than changes in precipitation. Most would agree that ranges of SLR can be estimated with confidence given historical data and knowledge of the changing climate. For those climate stressors that are more firmly founded on scientific study, the estimates of climate event occurrence that result from such studies can be used.
- ***Modified historical input data:*** Engineers use climate-related data as part of the engineering design process. For example, design parameters often include the design storm as the 100-year or 500-year storm. For drainage design, engineers use the intensity–duration curves to represent design precipitation events. These input parameters can be modified based on sound scientific reasoning to represent likely future weather events.
- ***General circulation models:*** Chapter 3 noted that most climate forecasts use many different models to predict future conditions, the so-called "ensemble" of models. It recommended that no one model result be used as ground truth in terms of future conditions, but rather a range of model results be used to represent plausible futures. The distribution of the individual models could be used (with necessary cautionary statements) as an indication of the likely occurrence of climate events. Model output should not be treated as probabilities. If, for example, 8 of 10 models in the ensemble project more intense storms in the forecast period, this *does not mean* there is an 80 percent chance of such an outcome, but it does show that most models project such a change. Such information can be considered in analyses of consequences and possible adaptations. It also should be noted that the "true uncertainty" is typically considered to be wider than the range of model output.

- **For asset failure**
  - ***Expert opinion:*** Most transportation agencies have engineering staff or consultants who are very familiar with the design of different assets. Based on years of experience with asset failures (e.g., culvert failures given intense precipitation), these engineers can provide an engineer's estimate of what it would take from a climate stressor perspective for a particular asset to fail. These failure estimates can then be used in conjunction with the probabilities of such stressor levels actually occurring.
  - ***Historical analysis:*** An agency could examine past records of asset failures given different weather and climate-related events. For example, a frequency curve over time showing the incidence of certain types of weather events and the resulting monetary damage to particular assets would in essence become a damage frequency curve. Such curves could be used to determine what monetary damage might occur with increasing frequency of such events in the future.
  - ***Engineering studies:*** For particular types of assets and/or for locations that might be particularly vulnerable to extreme weather events the agency could conduct engineering studies that would assess the current asset condition and determine expected failures given varying stressor levels. Such studies would identify different options that could be considered to reduce the potential for failure (see Chapter 6).

Given a particular climate scenario, where the probabilities of climate-related events and the probabilities of damage to assets are known or estimated, the costs and benefits of the performance of a system over a range of climate-related possibilities can also be estimated by using expected values. This approach is in essence creating different decision tress or paths of possible outcomes. The estimated value of annual damages is "the sum across the set of all possible damaging events of the product of the likelihood of a given event and the damages associated with it. Yearly expected value damage estimates are summed to estimate the total expected value over the planning period, with or without discounting as desired" (Kirshen et al. 2012). Of course, the probabilities of the climate event and asset failure will not likely stay the same each year, and the economic costs associated with failure will also not likely remain static. Indeed, the probability of failure could well increase over time, resulting in an increase in the expected value. This approach has been used in water resources planning for decades (Haimes 2004).

In such an application, a probability of an emissions scenario actually occurring is not included in the analysis. Such probabilities are not usually available, and they are not needed. Scenarios can be combined with risk analysis to determine the expected values of the impacts. As noted in Kirshen et al. (2012), it is possible "to assign probabilities to the events in each single socioeconomic and climate scenario even though it is not possible to assign probabilities to the scenarios themselves occurring." Their example is SLR where "for every assumed rate of sea-level rise, the probabilities of storm surges of various elevations occurring can be determined. The adaptation option that performs best over all the possible scenarios becomes the preferred option."

In one sense, the summation of the expected annual costs over the given time period is the cost of not doing adaptive engineering now. These costs could be discount and a benefit–cost analysis used to determine whether it makes sense to spend dollars today to avoid climate-related failure in the future. Such an example is provided in Chapter 6.

How Can Climate Change Scenarios Be Used to Account for Uncertainty in Decision Making?

Incorporating climate change in transportation decision making for highway planning or design will likely be a challenging exercise. The very basis of climate science is that the rate of change will be unknown, variable, and accelerating. And, the response of the earth's ecosystem to higher emissions levels is built on a series of assumptions with wide potential variations, with each assumption having its own range of possibilities. The result of this reality is that there is a wide range of possible outcomes from climate models that could define the future. For precipitation in particular, there are wide variations in climate model outputs that identify possibilities that point to a future that is wetter, the same, or drier in some areas of the country, depending on the emission scenarios and models applied and the base assumptions on how temperature shifts impact the water cycle. By consequence, generating what could be described as an accurate predicted future for decision making will be a very hotly debated enterprise.

There is also the question for transportation professionals as to the appropriate use of a climate model, or even an ensemble of models, to predict temperature, rainfall, or SLR to a reasonable level of accuracy implied by the engineering design process. Climate models are intended to describe how the earth's systems will respond at the global level. Culling rainfall data from global model outputs (through regional or statistical downscaling) and applying it (as an example) to identify future rainfall patterns on which to base decisions at a drainage basin scale could be considered an exercise outside of its intended application.

However, recent events around the country seemingly indicate that some factor—be it changing climate conditions, natural variability, or higher than normal recurrence—is causing precipitation and storm surge damage (or in contrast significant drought) to occur at unprecedented rates. Evidence has been seen with extreme weather events in southern California, Vermont, Minnesota, Washington State, New York/New Jersey, the Mississippi Basin, and elsewhere that occur outside of historical records. Transportation professionals need to consider the potential risks to infrastructure from weather events such as these and how the future may be expected to be different from the historical record currently used to create the basis for design decision-making.

Additionally, there is the reality that many of the values applied today as part of daily design exercises have associated uncertainty that is often not recognized or anticipated. As an example of this, the National Oceanic and Atmospheric Administration (NOAA) in its documentation for the *NOAA Atlas 14: Precipitation-Frequency Distribution of the United States* included the following: "For the first time, the National Weather Service is providing confidence limits for the estimates to quantify uncertainty. This will allow users a greater understanding of the uncertainty and will thus improve the utility of the estimates in engineering and environmental design practice" (Bonnin et al. 2006).

Part of the planning, design, and operations and maintenance dialogue then needs to be conducted considering not a static single value, but rather a range of potential values that take into account potential variability associated with the current climatology or with climate change. These assessments should be based on design lives, variability of climate stressor, risk to the facility, and a benefit–cost assessment of various response strategies. Approaches in the near term and agency responses will be dependent on newly developed policies until a common approach is developed and accepted industry-wide. An example of scenarios to be considered as part of planning and design could include the following:

- Base condition—following typical procedures, applying historical records as part of design practice.
- High-value existing data—applying the maximum value from within the uncertainty limits for calculated design variables (see NOAA discussion in previous paragraph).
- Increased design year value—example, applying a 200-year storm value instead of a 100-year storm value.
- Shifted significant storm event—example, shifting the path of a recent regional storm event to have higher local impacts.
- Factored future values—based on 24-hour precipitation values from applied climate models; could include multiple model/emissions scenarios.

Each of these scenarios could be tested to derive climate variables and possible design responses. The dialogue resulting from this analysis should include the following:

- What is the potential cumulative loss of functioning of damage over the lifetime of the asset (infrastructure damage, economic loss, etc.)?
- If the potential costs are high, should the facility be designed to a higher standard as a matter of course (e.g., 500-year event vs. 100-year event), particularly if policies do not include an assessment of future change?
- What is the difference in cost associated with adaptation strategies added to the design to ensure system resiliency for each scenario?
- What are the incremental benefits associated with adaptive design, and what are the associated benefits (costs avoided)?

Summary

Performing a climate change–related risk assessment helps agencies better understand the potential consequences of climate change on transportation infrastructure and supports the selection and prioritization of adaptation strategies. There are many uncertainties inherent in characterizing climate-related risks, concerning both climate itself (the frequency, severity, and timeframe of future weather events) and the effects of climate events on infrastructure (asset resiliency). Climate risk approaches help transportation agencies manage this uncertainty and can be integrated into current short- and long-term transportation planning, asset management, and risk mitigation processes for both existing and planned infrastructure. No risk management approach can ensure against future catastrophe or, on the contrary, the unwise or unnecessary deployment of scarce resources. Nonetheless, the incorporation of climate risk into an agency's activities is a key step toward an agency's stewardship of transportation infrastructure.

Examples of incorporating risk into planning and decision making were presented in this chapter. The most appropriate approach for a particular study or agency effort will depend on the scale of the application (e.g., system-wide, network-wide, or project-specific), the level of sophistication of the tools/models being used, the availability of climate data and asset condition/failure data, and the role of partner agencies and the public. The Toronto environmental assessment tool, for example, was developed and applied through a very public process in which relevant public groups and partner agencies participated in the assessment process. An agency must decide whether and to what extent the adaptation planning effort and in particular the identification of risk will be part of a much broader planning process or whether it will be primarily oriented to the technical details of a broadened definition of asset management.

CHAPTER 6

Climate Change and Project Development

The previous chapters have looked at adaptation efforts in the early stages of project development, that is, planning and problem definition. Once the need has been established for taking some action, either as a stand-alone adaptation measure or as part of another project, a more systematic project development process begins. In simple terms, project development is the process of taking a transportation improvement from concept through construction.

State transportation agencies adopt their own project development process, one that has evolved over many years to include aspects of project design, public participation, and legislative requirements that are specific to that state. It is thus difficult to present one project development process that encompasses all aspects of what a state transportation agency might face when moving a project to completion. This chapter will examine two parts of the project development process that are common to all state efforts—environmental analysis (when appropriate) and engineering design. In most cases, project development also includes steps such as problem identification, planning, and project initiation that relate to how a project is initiated in an agency's project development process. It is assumed that most of the initiation efforts have been covered in previous sections of this guide.

How Can Climate Adaptation Be Considered in Environmental Analysis?

Considering climate adaptation in environmental analysis is in the early stages of development in the United States. Very few state transportation agencies have formally added climate change to topics that should be discussed as part of state environmental reviews, and the federal government has proposed guidance on how this can be done but has not issued regulations (outside of guidance to the federal agencies themselves). Federal guidance and the limited efforts of state agencies have most often relied on a checklist of questions or topics to determine whether climate stressors need to be considered as part of alternatives definition and adaptive designs. In many ways, the approaches suggested to date reflect the diagnostic framework presented in Figure I.2, only in a simpler form. It is important to note that in most cases the guidance has focused on projects that are large enough to likely have significant impacts on the affected environment.

A state transportation agency undertakes thousands of actions every year, not only construction projects, but also maintenance and operations activities. Environmental analysis will not likely occur for most of these efforts. However, where action is being taken to put in place infrastructure that will last a long time, and/or decisions are being made to change standard operating procedures in operations and maintenance due to persistent changed weather conditions, it seems reasonable to examine the potential climate stressors that will affect such agency actions. As described previously, most of the approaches developed to date have consisted of a checklist of questions relating to the potential change in the affected environment. This guide suggests the following approach, which is similar but related to the diagnostic framework in Figure I.2.

For projects with an expected project lifespan over *x* (say 30) years, answers to the following questions should be documented and used to recommend appropriate action during the more detailed engineering design phase of the study.

1. What *climate stressors* will affect the proposed action either directly or through effects on the surrounding ecology?
2. What are the *impacts of these stressors on the affected environment* for the action (and to what extent is any proposed action in an area vulnerable to climate change)?
3. What is the *risk to the asset and to the affected environment* given expected changing climatic conditions?
4. To what extent do these stressors *influence the desired characteristics of the proposed action* (e.g., efforts to avoid, minimize, or mitigate potential risks)?
5. What are the *recommended strategies for protecting the function and purpose* of the proposed action?

Washington State DOT Project Development Guidance

The Washington State DOT is one of the first state transportation agencies in the United States to develop project development guidance on climate change. As noted in the guidance, WSDOT "acknowledges that effects of climate change may alter the function, sizing, and operations of our facilities" (WSDOT 2012). To enable projects to serve as intended over a long time span, the guidance states that projects should be designed to perform under the variable conditions expected as a result of climate change. In the initial stages of project formulation, WSDOT staff is asked to think of ways to make the proposed projects more resilient to future climate impacts and severe storm events.

WSDOT proposes to include potential changes in climate in the assessment of the future affected environment. Past trends are no longer considered accurate for determining the future environmental conditions for a project. The following specific steps are recommended (WSDOT 2012):

1. "Examine the results of WSDOT's Climate Impacts Vulnerability Assessment for your project area. . . . This information will alert you to vulnerabilities and/or strengths in the existing WSDOT facilities"
2. "Contact WSDOT Environmental Services Policy Branch . . . for assistance in creating an up-to-date summary of climate threats in your project area"
3. "Direct project technical specialists to consider the available information (Steps 1 and 2) in their NEPA and SEPA analysis, as well as their proposals for mitigating impacts"
4. "Document your findings regarding anticipated climate threats in the cumulative effects section (if separate) or in specific discipline sections (Fish and Wildlife, Wetlands, Land Use, etc.)"
5. "Document how the project will be designed to be resilient or resistant to climate threats (such as the use of drilled shafts or site selection to avoid a potential threat)"

The guidance also provides the following draft language to be incorporated into project initiation documents and environmental reports, where appropriate (WSDOT 2012):

> "The project team considered the information on climate change with regard to preliminary design as well as the potential for changes in the surrounding natural environment.
>
> The project is designed to last (30, 50, 70) years. As part of its standard design, this project has incorporated features that will provide greater resilience and function with the potential effects brought on by climate change."

Once these five questions are answered and documented, the more detailed engineering design can begin.

The level of analysis that is used to answer these questions will depend on the requirements of federal or state law, the data and information that are already available (such as climate data for the state from an independent source), the likely significance of the environmental impacts and the impacts on the affected environment, and the level of resources available to conduct an environmental analysis. Any environmental analysis that examines potential impacts and identifies likely mitigation strategies will include engineering details sufficient to determine which strategies make most sense for the project-specific context. Engineering design thus becomes an important focus for a climate change–oriented adaptive design approach.

How Is Engineering Design Adapted to Constantly Changing Climate?

What pipe diameter is necessary for a culvert to function properly? What asphalt mix will minimize pavement life-cycle costs? How deep must a bridge's foundation be to protect it from scour brought about by coastal storm surge? All of these questions, and many others addressed daily by engineers, involve assumptions about the climate of the future. Traditionally, the working assumption has been that future climate conditions will be similar to those of the past and that historical observation is a reliable predictor of what is to come. With climate change, this is no longer true (Meyer 2006).

How can engineers adapt their practices to a constantly changing climate? To address this question, a series of tables along with a decision support tool have been developed that show how adaptation can be incorporated into the planning and design of specific asset types. Detailed tables include specific guidance for bridges, culverts, stormwater infrastructure, slopes/walls, and pavement. The tool was developed to provide a more user-friendly method of using the information from the tables, specifically as it related to project-level decisions. The tool is a query-based system that provides focused results for a particular asset class and climate threat. The tool and tables are provided on the accompanying CD-ROM. For purposes of illustration, the tables relating to culverts are presented in this section.

Tables I.8 to I.10 present the information that can be found in the adaptive design approach for culverts. Table I.8 presents information on the input variables that are used to calculate key design parameters. For example, Table I.8 shows more extreme rainfall events will likely affect stream flows, which is a critical design variable for culvert design. In this case, the method used for estimating stream flow relies on 24-hour precipitation, intensity–density–frequency (IDF) curves, and precipitation distribution input values. The table then shows preferred and alternative sources of input values given potential changes in precipitation.

Table I.8. Climate-dependent input parameters for culvert design.

First-Order Climate Variable (Columns B and C)		**Second-Order Climate Variable (If Applicable)** (Column D)	**Method for Estimating the Second-Order Climate Variable (If Applicable)** (Column E)	**Affected Design Input** (Column F)	**Typical Source(s) of Referenced Design Input** (Column G)	**What Future Value to Use for the Affected Design Input?** (Column H)
Precipitation	***More extreme rainfall events***	Stream flows (2 -100 year recurrence intervals)	Theoretical models (TR-20, TR-55, HEC-HMS, rational method)	24-hour precipitation for given recurrence interval	NOAA Atlas 14 or TP-40	**Preferred:** Utilize downscaled projected climate change precipitation values. **Alternative:** Use relative increases in precipitation amounts following the Clausius–Clapeyron relationship.[1]
				IDF curves	NOAA Atlas 14, TP-40, or state-specific sources	**Preferred:** Utilize projected IDF curves reflecting projected climate change if available.[2] **Alternative:** Use relative increases in precipitation totals following the Clausius–Clapeyron relationship.[1]
				Precipitation distribution[3]	NRCS-type curves or state-specific curves	**Preferred:** Utilize projected precipitation distribution type curves from climate models. **Alternative:** Assume no changes and utilize existing curves.
			Regional regression curves	Shape of regional curve[4]	USGS or state-specific sources	**Preferred:** Utilize regional curves with considerations for climate non-stationarity. **Alternative:** Utilize theoretical models instead.
			Stream gauge analysis	Shape of historical data curve[5]	USGS or local sources	**Preferred:** Utilize stream gauge analyses with data adjustments using regional curves with considerations for climate non-stationarity. **Alternative:** Utilize theoretical models instead.
	Greater snowfall depths	Stream flows (2 -100 year recurrence intervals)	Regional regression curves	Shape of regional curve[4]	USGS or state-specific sources	**Preferred:** Utilize regional curves with considerations for climate non-stationarity. **Alternative:** Adjust results of existing regression analyses by a percentage correlated to anticipated snowpack increase.
			Stream gauge analysis	Shape of historical data curve[5]	USGS or local sources	**Preferred:** Utilize stream gauge analyses with data adjustments using regional curves with considerations for climate non-stationarity. **Alternative:** Adjust results of historical gauge analysis by a percentage correlated to anticipated snowpack increase.

(continued on next page)

Table I.8. (Continued).

First-Order Climate Variable (Columns B and C)		Second-Order Climate Variable (If Applicable) (Column D)	Method for Estimating the Second-Order Climate Variable (If Applicable) (Column E)	Affected Design Input (Column F)	Typical Source(s) of Referenced Design Input (Column G)	What Future Value to Use for the Affected Design Input? (Column H)
Water Level / Chemistry	***Sea-level rise***	–	–	Base tidal elevation	NOAA tidal buoys	**Preferred:** Increase local tidal datums by projected SLR.
				Fresh vs. saline water	Local knowledge	**Preferred:** Increase local tidal datums by projected SLR and determine whether freshwater is likely to become saline.
	Lake-level rise	Base lake level	Theoretical water budget models	Water depth	Historical data	**Preferred:** Increase average local lake level by the projected lake-level rise as forecast from a revised water budget model. **Alternative:** Investigate historical response of lake levels to years with high annual precipitation. Extrapolate lake level trends to projected annual precipitation levels.
	Lake-level decrease	Stream channel geomorphology	Theoretical considerations and historical data evaluation	Long-term bed scour	Historical surveys, observed channel characteristics, and/or geomorphic surveys	**Preferred:** Adjust stream channel profiles with considerations for lake-level decrease determined from a climate change–influenced water budget model. **Alternative:** Investigate historical response of lake levels to droughts and years with lower annual precipitation. Extrapolate lake-level trends to projected maximum drought periods or lower annual precipitation projections.
	Increase in ocean salinity	–	–	Water chloride level	Water samples	**Preferred:** Use projected chloride levels over asset life span based on climate research.
	Ocean acidification	–	–	Water pH	Water samples	**Preferred:** Use projected maximum pH over asset life span from climate research.

[1] The Clausius–Clapeyron relation shows that the water-holding capacity of the atmosphere increases by about 7 percent per degree Celsius increase in temperature (or 4 percent per degree Fahrenheit) (Committee on Hydrologic Science 2011). While the interactions among climatology, temperature increases, and precipitation changes are significantly more complex, the use of the relationship provides a simplified basis for incorporating climate change into precipitation-based designs for cases where localized yearly average temperature changes are available, but precipitation changes are not. Results from the application of this method are anticipated to be conservative given the limited considerations of the method, but could provide a starting point for the incorporation of climate change into engineering design.

[2] See Solaiman and Simonovic (2011) and the Canadian Standards Association for guidance on how IDF curves can be generated for various climate change scenarios using weather generators and other analytical techniques.

[3] Precipitation distribution curves such as the SCS Type I, IA, II, and III curves (refer to the Natural Resources Conservation Service), which are correlated to the shape of IDF curves, have been developed based upon historical observations of storm patterns throughout defined regions of the United States.

[4] Traditional regional regression curves have been developed based upon historical stream gauging records within similar watershed basins in the same physiographic province. Climate change science contradicts the stationarity assumption that is inherent in the usage of historical data as the basis for prediction of future events.

[5] As with regional regression curves, the use of historical stream gauging data combined with a Log-Pearson Type III (or other) statistical distribution assumes a condition of stationarity that does not incorporate climate change considerations.

Table I.9 presents information for new infrastructure adaptation options. For example, Table I.9 indicates that for more extreme rainfall events and greater snowfall depths, increasing culvert size, using a small bridge instead of a culvert, or using a larger scour pool or rip rap could be considered. In addition, the table shows how future flexibility could be incorporated into a traditional design that might have to be retrofit in the future given changed flow characteristics.

Table I.10 presents information for retrofitting or reconstructing existing infrastructure. In the case of more extreme rainfall events, two design characteristics—hydraulic sizing and outfall scour protection—can be changed in the future if the existing design proves inadequate. This change might include adding additional culverts, replacing with a larger culvert, adding headwalls and end walls, installing scour protection, and installing debris guards and/or outfall scour protection.

Readers should be aware that the engineering design information found in the tables and tool was synthesized from best practice for each type of asset or facility. Those states with design standards or guides that differ from what is presented are encouraged to modify the tables as appropriate. Information is presented for both new infrastructure and for modifying existing infrastructure.

The following adaptive engineering analysis consists of a six-step process. Realizing that each agency and each engineering discipline has its own perspectives on the design process, the process presented here is generalized so that it can apply broadly. It is also flexible enough that it can be used for the design of new assets or the retrofitting of existing assets. The remainder of this section describes the recommended approach for an adaptive engineering step-by-step analysis.

Step 1: Review Environmental and Institutional Setting and Project Requirements

The first step of the adaptive engineering analysis involves reviewing the project setting, essentially, getting a lay of the land. This step involves paying close attention to aspects of the environment that could be affected by climate change. Key things to look for include proximity to wetlands, streams, lakes, and the sea; low spots where water might tend to accumulate; and steep slopes that could pose a landslide hazard.

Step 1 also includes reviewing the project's institutional setting. It is important to identify all of the stakeholders that have a role in project development (including federal, state, and local agencies) and to determine what, if any, policies exist on climate adaptation. Summarizing the various adaptation policies will be useful in identifying potential conflicts and opportunities when considering adaptive design solutions. In some cases, understanding others' adaptation policies may help to determine whether adaptive solutions would even be necessary. For example, all projects in coastal areas should be aware of the sea-level rise policy of the U.S. Army Corps of Engineer (USACE) and how adaptation has been considered in any USACE activities affecting one of its projects (USACE 2011). It is possible that an existing or planned USACE action may already account for sea-level rise and would lesson or eliminate the threat it poses to the project.

Understanding the project requirements, another key component of Step 1, helps in the development of adaptation options in subsequent steps. In particular, the required or remaining design life of the facility should be noted in this review. In most cases, the time horizon for the adaptive engineering analysis should be made to correspond with the facility's design life. This will ensure that the design will be evaluated against the full range of climate stressors it will be exposed to over its lifespan.

Table I.9. Adaptation options for new culverts.

First-Order Climate Variable (Columns B and C)		**Affected Design Components** (Column I)	**New Infrastructure Adaptation Options**					
			Traditional Design Option with Climate Model Inputs			**Alternative Design Options**		
			Practical Effect on Asset (Column J)	Cost (Column K)	Special Considerations (Column L)	Design Option (Column M)	Cost (Column N)	Special Considerations (Column O)
Precipitation	***More extreme rainfall events***	Hydraulic sizing for culvert openings / number of openings Design of outfall scour protection	Increased culvert size and/or more openings	Low to moderate	Initial over-sizing could cause sedimentation in culvert	Obtain right-of-way (ROW) and access routes to allow for culvert retrofit	Low to moderate	–
	Greater snowfall depths		Larger scour pools and larger riprap	Low		Use of a bridge instead of a culvert	Moderate	
Water Level / Chemistry	***Sea-level rise***	Tailwater elevations for hydraulic sizing of culverts Materials selection	Increased culvert size and/or more openings (for culverts operating in tailwater conditions)	Low to moderate	Potential for upstream flooding increases during coastal storm surges[1]	Obtain ROW and access routes to allow for culvert retrofit	Low to moderate	–
			Consideration of more saltwater-resistant materials in currently freshwater environments	Low				
	Lake-level rise	Tailwater elevations for hydraulic sizing of culverts	Increased culvert size and/or more openings (for culverts operating in tailwater conditions)	Low to moderate	Potential for upstream flooding increases during storm surges[1]	Obtain ROW and access routes to allow for culvert retrofit	Low to moderate	–
	Lake-level decrease	Design considerations for long-term scour at culvert outfall	Depth of culvert end wall foundation	Moderate	Perching of culvert due to long-term scour will create an aquatic organism passage obstruction	–	–	–
	Increase in ocean salinity	Material specifications for structural components Specifications for protective liner/coatings	More acidic/chloride-resistant materials	Low to moderate	–	–	–	–
	Ocean acidification		Added or modified liner/protective coatings	Low to moderate				

[1] Increased hydraulic conveyance of stream crossings, while providing a beneficial reduction in flooding due to upland flooding sources, may also allow increased conveyance for the propagation of storm surge upstream.

Table I.10. Adaptation options for existing culverts.

First-Order Climate Variable (Columns B and C)		Affected Design Components (Column I)	Existing Asset Adaptation Options		
			Retrofitting Options		
			Retrofit Option (Column P)	Cost (Column Q)	Special Considerations (Column R)
Precipitation	***More extreme rainfall events***	Hydraulic sizing for culvert openings / number of openings Design of outfall scour protection	Add additional culverts	Moderate to high	Potential liability for increases in downstream flooding.[1]
			Pipe jack and replace with larger culvert	Moderate	
			Add headwall and end wall[2]	Low to moderate	
			Install roadway overtopping scour protection[3]	Low	
			Install debris guards/ racks upstream[4]	Low to moderate	Environmental coordination and mitigation might be necessary. Increased maintenance frequency. Potential liability to upstream flooding increases.
	Greater snowfall depths		Upsize and replace outfall scour protection measures	Low	
Water Level / Chemistry	***Sea-level rise***	Tailwater elevations for hydraulic sizing of culverts Materials selection	Add additional culverts	Moderate to high	Potential for upstream flooding increases during coastal storm surges.[5]
			Add additional culverts	Moderate to high	
			Pipe jack and replace with saltwater-resistant pipe(s)	Moderate	
	Lake-level rise	Tailwater elevations for hydraulic sizing of culverts	Add additional culverts	Moderate to high	Potential for upstream flooding increases during storm surges.[5]
			Pipe jack and replace with larger culvert	Moderate	
	Lake-level decrease	Design considerations for long-term scour at culvert outfall	Incorporate stream restoration design with grade control structures along the channel bed	High to very high	Restoration of channel and reduction of sediment sources will provide an uplift to the quality of an impaired system.
	Increase in ocean salinity	Material specifications for structural components	Add protective liner/ coating	Moderate	–
	Ocean acidification	Specifications for protective liner/coatings			

[1] Increases in downstream flooding have a potential to occur for scenarios where an undersized stream crossing is creating upstream storage areas and attenuating peak flow rates to downstream areas.

[2] For cases of pipe projecting from fill

[3] For armoring of roadway embankment fill that may become vulnerable to erosion and mass wasting due to increased frequency of overtopping of roadway or increased depth of overtopping flow over roadway.

[4] Debris racks as a retrofit would provide benefits to current culvert crossings that have a history of debris clogging issues and may become more vulnerable to failure under changing climate scenarios.

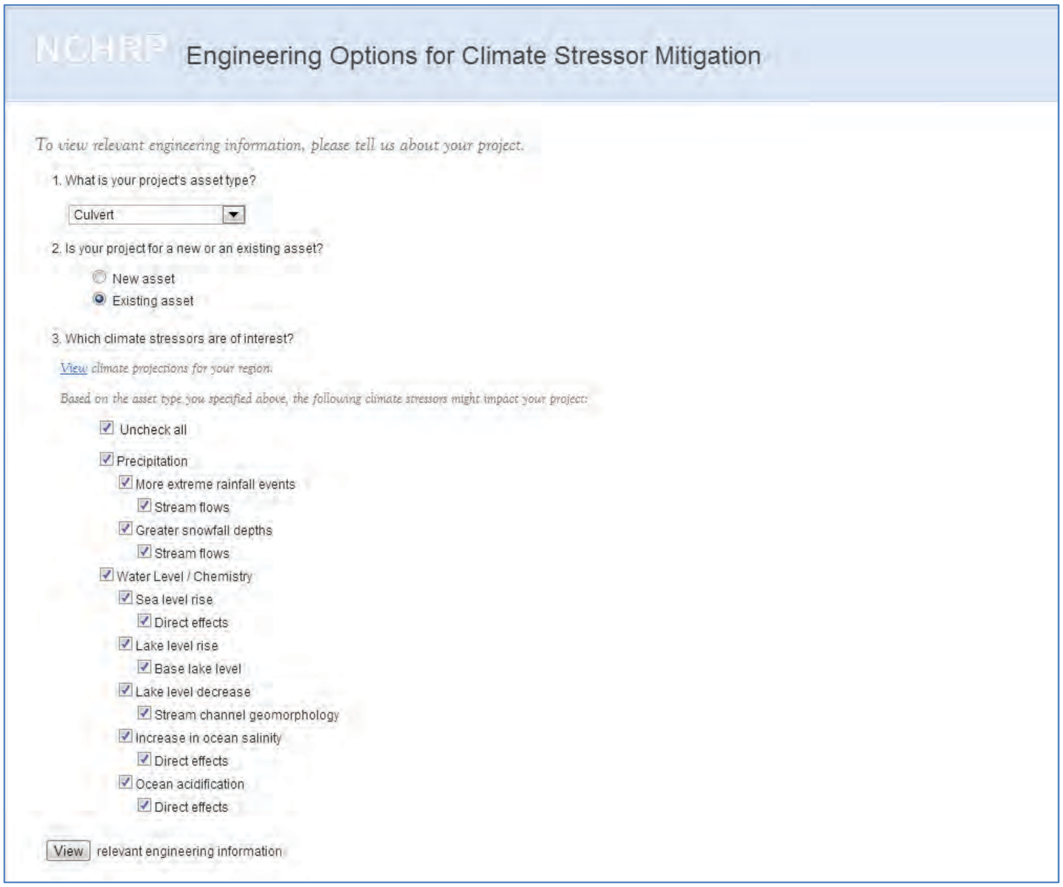
[5] Increased hydraulic conveyance of stream crossings, while providing a beneficial reduction in flooding due to upland flooding sources, may also allow increased conveyance for the propagation of storm surge upstream.

Step 2: Identify the Possible Climate-Affected Design Parameters for the Given Asset Type

Step 2 of the analysis identifies the specific climate stressors to which the project will likely be subject. The detailed tables in the spreadsheet and the decision support tool on the accompanying CD-ROM can assist in this effort. To use them, first identify the asset type(s) relevant to the project: bridges, culverts, stormwater infrastructure, slopes/walls, and/or pavement. Next, select the corresponding tab(s) in the spreadsheet or asset type from the drop-down menu in the tool on the CD-ROM.

Within each asset table, the First-Order Climate Variable columns (Columns B and C) provide a list of all the possible climate stressors relevant to that asset type. Within the tool, relevant climate stressors are listed under item 3 (see Figure I.13). For example, culverts may be at risk from precipitation-related stressors like more extreme rainfall events and greater snowfall depths. Culverts are also susceptible to water-level and chemistry-related stressors such as sea-level rise, lake-level rise, increases in ocean salinity, and ocean acidification.

In some cases, the potential threat to the asset is manifested not through the first-order climate threat, but through associated second-order effects. With culverts, for example, more extreme rainfall events themselves are not so much the hazard as are the higher peak stream and drainage flows associated with those events. The presence of a second-order climate stressor is shown in the tables under the Second-Order Climate Variable column (Column D); in the tool, second-order climate stressors are shown when a first-order climate stressor is selected.



Engineering Options for Climate Stressor Mitigation

To view relevant engineering information, please tell us about your project.

1. What is your project's asset type?

Culvert ▼

2. Is your project for a new or an existing asset?

○ New asset
● Existing asset

3. Which climate stressors are of interest?

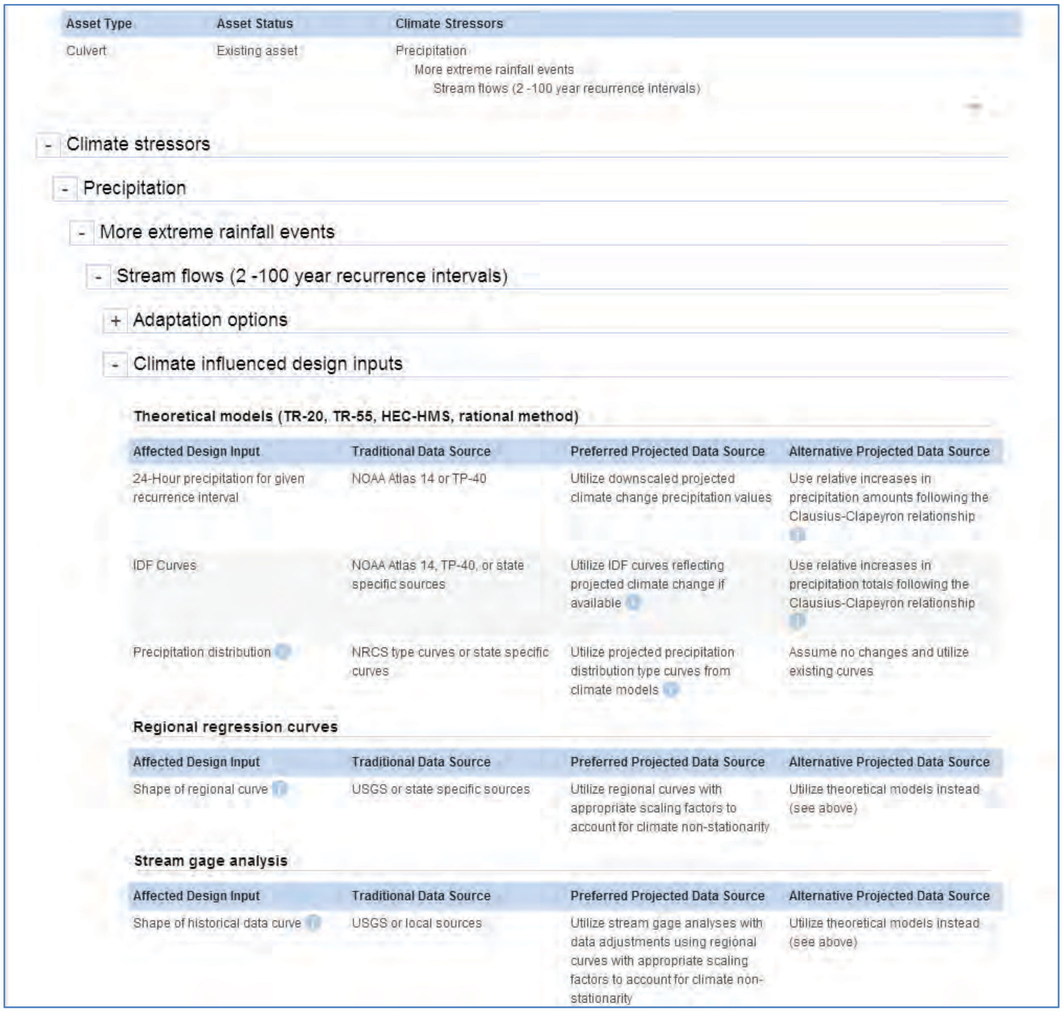
View climate projections for your region.

Based on the asset type you specified above, the following climate stressors might impact your project:

- ☑ Uncheck all
- ☑ Precipitation
  - ☑ More extreme rainfall events
    - ☑ Stream flows
  - ☑ Greater snowfall depths
    - ☑ Stream flows
- ☑ Water Level / Chemistry
  - ☑ Sea level rise
    - ☑ Direct effects
  - ☑ Lake level rise
    - ☑ Base lake level
  - ☑ Lake level decrease
    - ☑ Stream channel geomorphology
  - ☑ Increase in ocean salinity
    - ☑ Direct effects
  - ☑ Ocean acidification
    - ☑ Direct effects

relevant engineering information

Figure I.13. Initial project selection page of the decision support tool.



Asset Type	Asset Status	Climate Stressors
Culvert	Existing asset	Precipitation More extreme rainfall events Stream flows (2 -100 year recurrence intervals)

- Climate stressors
  - Precipitation
    - More extreme rainfall events
      - Stream flows (2 -100 year recurrence intervals)
        - + Adaptation options
        - - Climate influenced design inputs

Theoretical models (TR-20, TR-55, HEC-HMS, rational method)

Affected Design Input	Traditional Data Source	Preferred Projected Data Source	Alternative Projected Data Source
24-Hour precipitation for given recurrence interval	NOAA Atlas 14 or TP-40	Utilize downscaled projected climate change precipitation values	Use relative increases in precipitation amounts following the Clausius-Clapeyron relationship
IDF Curves	NOAA Atlas 14, TP-40, or state specific sources	Utilize IDF curves reflecting projected climate change if available	Use relative increases in precipitation totals following the Clausius-Clapeyron relationship
Precipitation distribution	NRCS type curves or state specific curves	Utilize projected precipitation distribution type curves from climate models	Assume no changes and utilize existing curves

Regional regression curves

Affected Design Input	Traditional Data Source	Preferred Projected Data Source	Alternative Projected Data Source
Shape of regional curve	USGS or state specific sources	Utilize regional curves with appropriate scaling factors to account for climate non-stationarity	Utilize theoretical models instead (see above)

Stream gage analysis

Affected Design Input	Traditional Data Source	Preferred Projected Data Source	Alternative Projected Data Source
Shape of historical data curve	USGS or local sources	Utilize stream gage analyses with data adjustments using regional curves with appropriate scaling factors to account for climate non-stationarity	Utilize theoretical models instead (see above)

Figure I.14. Climate-influenced design inputs.

When a second-order climate variable exists, engineers have often developed various approaches to model that variable. These are listed in Column E of the table, Method for Estimating the Second-Order Climate Variable, and under the heading Climate Influenced Design Inputs on the relevant engineering information page of the tool (see Figure I.14). For example, stream flows for culverts can be estimated using three different techniques: theoretical models, regional regression curves, or stream gauge analysis.

Whether the threat to the asset is manifested through a first- or a second-order climate stressor, the Affected Design Input column (Column F) lists the specific climate parameters used in the design process. Ideally, engineers would like to have both the historical and projected future values for each of these parameters. At the conclusion of this step, the engineer should have a sense of the climate stressors that could affect the project along with a list of the specific climate-related design inputs that will need to be evaluated for changes.

Step 3: Review Past Climate Trends and Obtain and/or Calculate Climate Projections

Step 3 involves obtaining and/or developing the specific climate parameters listed in Step 2. To set a baseline for measuring change, it is important to first obtain the historical values of these parameters from the sources traditionally consulted by engineers. These sources are listed in the tables under Column G, Typical Source(s) of Referenced Design Input, and in the tool under the column Traditional Data Source. Once the historical data has been obtained, attention can turn towards the potentially difficult step of finding projected values of those same climate parameters over the time horizon of the analysis (i.e., the remaining design life of the facility).

Unfortunately, today's climate models do not generally output the climate parameters that feed directly into design processes; some translation and derivation of their outputs are often required. In many cases, this work may be beyond the scope and budget of transportation agencies. In other cases, the scientific understanding of how the parameters respond to climate change is still too uncertain to make defensible projections. Addressing both of these major hurdles will require additional research and state and national efforts to help translate climate model outputs en masse into actionable parameters useful to engineers. In the meantime, transportation agencies still need to make design decisions and determine if change is coming and, if so, what its potential magnitude may be.

With this in mind, Column H of the tables (What Future Values to Use for the Affected Design Input) and the Projected Data Source columns in the tool present both preferred and alternative means of obtaining each design parameter. The preferred method represents the ideal approach if projections are available. However, if they are not available, the alternative method, usually involving more assumptions and generalizations, can be used in the interim. For example, the theoretical model approach to estimate stream flows for culvert design would, under the preferred technique, make use of projected future IDF curves. However, projected IDF curves are not yet available for much of the United States. An alternative approach would be to make use of the Clausius–Clapeyron relationship. This relationship, which correlates temperature with the water-holding capacity of the atmosphere, could be loosely projected onto the relationship between temperature and precipitation events. Use of the relationship is anticipated to yield a conservative result, as the relationship between climatology and precipitation events is significantly more complex, but the method can provide a starting point for the scaling of precipitation data.

The temporal aspect of climate change should also be appreciated when obtaining future projections. Projections for 2050 are not likely to be the same as those for 2075 or 2100. With this in mind, the values of the parameters should be obtained for multiple time periods in the asset's design life so that a trend line can be developed. At a minimum, this might involve projections for the end of the design life and a point in between. If appropriate, this work should also be repeated for multiple greenhouse gas emissions scenarios. Agencies will need to determine, based on their aversion to risk, whether to consider all emissions scenarios; a low, mid-range, and high scenario; a single scenario; or some other combination. The best practice in the emerging field of climate adaptation is to use an ensemble approach with multiple emissions scenarios. Once the historical and projected climate parameters have been obtained, a comparison should be made with a trend line developed over the asset's design life. A decision can then be made as to whether the parameter's trend line indicates enough change to warrant adaptive actions and, if so, what year's parameter value will be used in the design. Choosing the parameter value for the end of the asset's design life is advantageous because it provides some insurance in case (1) climate change happens faster or more severely than anticipated (a growing realization) or (2) the facility is called upon to outlast its intended design life.

Step 4: Identify the Design Components Affected by Changes in Climate

Step 4 answers the question, "Given that parameters *x*, *y*, and *z* from Step 3 will be changing, where are the vulnerabilities in the proposed design?" Understanding how each of the parameters affects the design is critical to determining what adaptive actions can be taken in later steps. In the tables, each parameter's impacts on design are shown in the Affected Design Components column (Column I). For example, stream flows affect the hydraulic sizing of culvert openings (or the number of openings) and the design of outfall scour protection.

Step 5: Determine Adaptation Options

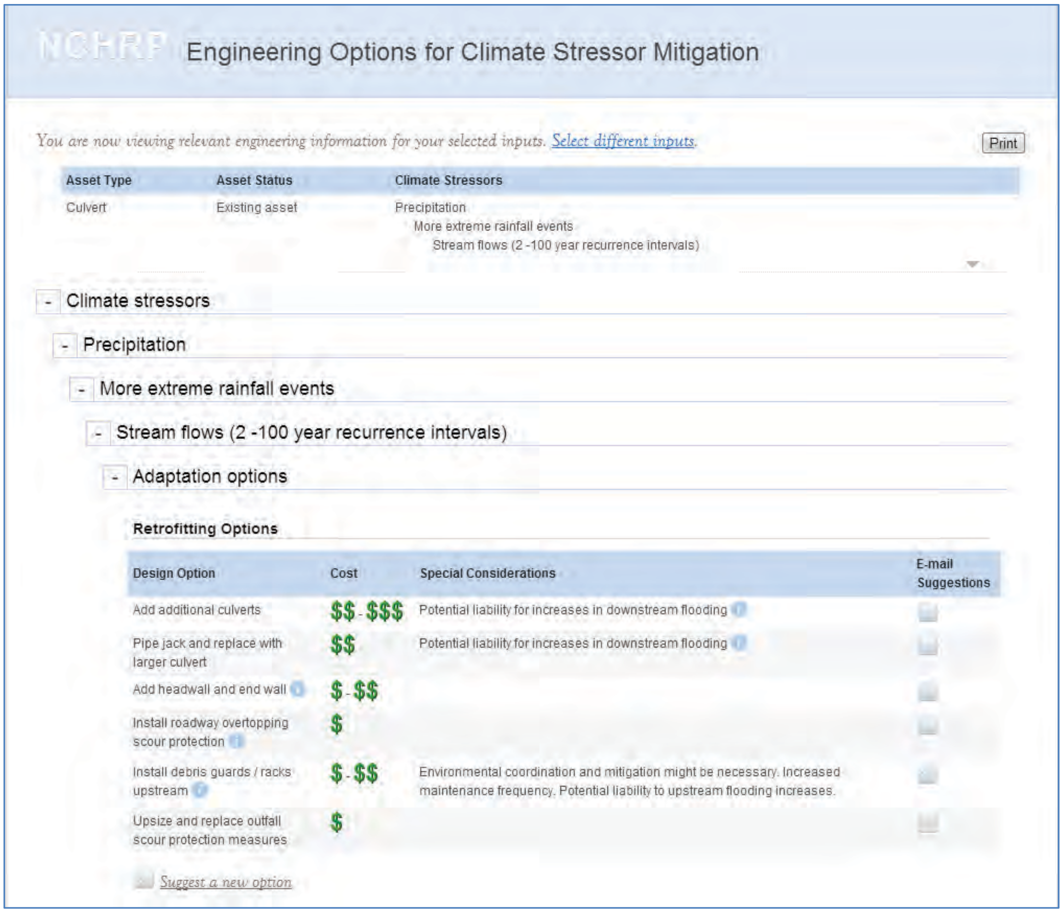
Step 5 consists of developing adaptation options that reduce the vulnerabilities identified in Step 4. Along with the adaptation options themselves, this step requires the selection of an approach for evaluating which adaptation options make sense. The approach determines how many adaptation options will be developed for the engineering analysis.

One option is a scenario approach whereby multiple design alternatives are compared against multiple possible climate futures to assess which alternative has the highest benefit–cost ratio over its design life. If an agency chooses this approach, some extra time and resources will be required to develop multiple alternative designs to a sufficient level of detail to allow accurate comparisons of benefits and costs. Alternatives could consist of (1) an adaptation and a no-adaptation alternative to determine if the adaptation is worth the extra cost and/or (2) multiple adaptation alternatives to determine which level of protection (adaptation) makes the most sense financially. Although the scenario approach entails more up-front analysis work, the long-term payoffs could be substantial. In addition, tools are being developed to help lessen the burden of conducting these evaluations. For example, see the U.S. Environmental Protection Agency's set of water-related tools for analyzing benefits and costs in the context of climate change (http://water.epa.gov/type/oceb/cre/toolkit.cfm). USACE recognizes the benefits of a scenario approach and now requires that for certain USACE activities three sea-level rise scenarios be taken into account and design/planning alternatives be created for each of them. These alternatives are then evaluated across the range of scenarios using multiple criteria including, optionally, benefit–cost analyses.

Alternatively, if an agency has limited resources to engage in scenario analysis and there is a supportive political environment for adaptation, it may choose to forgo a full scenarios analysis and commit to a single future climate scenario of its choosing. In some cases, an agency may be required to do this if a higher level of government has preselected a climate scenario to use for planning and design purposes. In these cases, only one design alternative needs to be developed, the adaptive design. Although there is an appeal to the simplicity and efficiency of this approach, there is also a heightened risk that the chosen design may not be the most cost-effective in the long run.

Once an approach has been determined, attention can turn to the development of the adaptation option(s). Experience, ingenuity, and creativity will all prove helpful at this stage of the analysis as adaptive engineering is a new practice and there are very few examples of adaptive designs to emulate. In the tables and the tool, an attempt has been made to provide some general adaptation ideas for each of the potential climate stressors listed. These ideas should only be viewed as a starting point for discussion; engineers will have to judge their suitability on a project-by-project basis. Also these ideas should not be seen as a comprehensive list of adaptation options. Undoubtedly, many more possibilities exist and these lists will be added to as adaptation awareness spreads within the engineering community.

The tables and the tool differentiate the adaptation options by their application to existing or new assets. The tool will display adaptation options relevant to existing or new assets (see Figure I.15) based on the selections made on the initial project selection page. In the tables, guidance on adapting existing assets is presented in Columns P through R (see Table I.10). Column P, Retrofit Option, presents general retrofitting strategies for each climate-sensitive design



Engineering Options for Climate Stressor Mitigation

You are now viewing relevant engineering information for your selected inputs. Select different inputs.

Asset Type	Asset Status	Climate Stressors
Culvert	Existing asset	Precipitation More extreme rainfall events Stream flows (2 -100 year recurrence intervals)

- Climate stressors
  - Precipitation
    - More extreme rainfall events
      - Stream flows (2 -100 year recurrence intervals)
        - Adaptation options

Retrofitting Options

Design Option	Cost	Special Considerations	E-mail Suggestions
Add additional culverts	$$ - $$$	Potential liability for increases in downstream flooding	☐
Pipe jack and replace with larger culvert	$$	Potential liability for increases in downstream flooding	☐
Add headwall and end wall	$ - $$		☐
Install roadway overtopping scour protection	$		☐
Install debris guards / racks upstream	$ - $$	Environmental coordination and mitigation might be necessary. Increased maintenance frequency. Potential liability to upstream flooding increases.	☐
Upsize and replace outfall scour protection measures	$		☐

Figure I.15. Adaptation options for existing culverts (from the decision support tool).

component. Retrofitting involves making a physical adjustment to an existing design to accommodate projected changes in the design parameters. This strategy is an option in many, but not all, cases where an existing asset is threatened. In some cases, especially those involving foundations, retrofitting options are not likely to be viable and the column is left blank. In these cases (and even those where retrofits are possible), it is worthwhile exploring whether other adaptation options make sense. For any existing asset, these alternatives include (1) completely rebuilding the asset in either the same place or in a nearby location removed from the vulnerable location, (2) abandoning the asset, or (3) implementing non-design or non-transportation-design solutions (e.g., a levee or surge barrier may be a better alternative than raising a road elevation in some locations). Option 2 might be most applicable in situations where a road serves an area that is becoming permanently inundated by rising seas. Since these three options apply universally, they are not presented in the table but they should always be part of the alternatives development process.

Columns Q and R, Cost and Special Considerations, are a continuation of the retrofit options in Column P and provide cost approximations and special considerations for the corresponding retrofit option. For example, when considering how to retrofit a culvert that is (or may be) experiencing issues due to higher stream flows, one retrofit option entails adding additional culverts. In Columns Q and R, the corresponding information shows that this retrofit option has moderate to high costs and special consideration needs to be made for downstream flooding liabilities (see Table I.10). The costs for the adaptation options shown throughout the tables and tool are intended for relative order-of-magnitude comparisons only. They are defined as a percentage of the total costs to construct a business-as-usual non-adaptation alternative:

low ($ in the tool) corresponds to a 1 to 5 percent addition in total asset cost, moderate ($$) corresponds to 6 to 10 percent, high ($$$) 10 to 25 percent, and very high ($$$$) greater than 25 percent. There are also a few cases where there are likely to be no cost increases or a cost savings and these are noted as well.

In the tables, adaptation options for new infrastructure are presented in Columns J through O (see Table I.9). The Costs and Special Considerations columns (K, L, N, and O) are organized in a similar way to their counterparts in the retrofit options for existing assets described in the previous paragraph. The key difference is that for new infrastructure two adaptation options are shown: (1) Traditional Design Options with Climate Model Inputs (Columns J through L) and (2) Alternative Design Options (Columns M through O). The first option involves following traditional design practice, but using climate model projections for the design parameters instead of historical data. With this approach, adaptations are fully implemented at the time of initial construction. The alternative design option columns, on the other hand, highlight design approaches that might differ substantially from an agency's traditional practice. These approaches include the option of using a completely different asset type or design, one that is more resilient to climate stressors, than would normally be employed (e.g., a tunnel instead of a rock cut or use of an open grate bridge. These columns also include flexible design options (sometimes referred to as "adaptive design options") that recognize the uncertainties in climate projections and, instead of fully building the adaptation now, incorporate the flexibility to more easily retrofit the asset in the future if conditions warrant. With flexible design, a smaller amount of money is spent up-front on adaptation and the possibility of over-adapting (i.e., spending too much on an adaptation that turns out not to be needed) is lessened. This approach is highly promising given the uncertainties in climate projections and is worthy of further research and creative development.

As with existing assets, the two approaches shown in the tables and the tool are not the only adaptation options available for new infrastructure. There might be non-design solutions to the problem worth considering or design solutions beyond those focused on transportation infrastructure. Another option, perhaps the least risky of all, is to avoid the asset vulnerability altogether if feasible. This is a planning-level item that should be considered early in the project development process. For example, if a new road is originally planned to follow a river valley subject to higher projected stream flows, the possibility of re-routing parts or all of the alignment to non-flood prone areas should be considered. Another new infrastructure adaptation option is shortening the design life of the asset (or parts of the asset) relative to standard practice. By shortening the design life, the exposure of that asset to long-term climate change, and the uncertainty of that change, is lessened. This approach might be most appropriate when a new asset is required to serve an area projected to be permanently inundated by sea-level rise within the timeframe of a typical standard design life.

At the conclusion of Step 5, the engineer should have adaptive design alternative(s) developed to a preliminary engineering level of detail and, possibly, a no-adaptation alternative as well. If a scenario-based benefit–cost approach is taken, the adaptation engineering assessment moves on to Step 6. If a single scenario has already been pre-selected, then the assessment is complete and the adaptation option developed in Step 5 can be taken to the final design stage.

Step 6: Conduct a Scenario-Driven Benefit–Cost Analysis (optional)

The final step in the engineering assessment involves evaluating the performance of the adaptation alternatives developed in Step 5 across the range of climate scenarios obtained in Step 3. One possible organizing framework for the evaluation is a benefit–cost analysis of the alternatives to determine (1) whether taking adaptive action is prudent and, if so, (2) how much protection that adaptive action should afford. A benefit–cost analysis will provide a metric for comparing the different project alternatives: whichever alternative has the highest incremental benefit–cost ratio should be seen as the best option from a climate change adaptation perspective. Obviously, as with any transportation project, the alternatives analysis will need to consider other environmental and social factors as well.

FHWA's *Economic Analysis Primer* already treats the incorporation of risk adjustment factors into economic analysis to help manage the fundamental uncertainties associated with transportation projects, either through sensitivity analysis (the adjustment of specific variables associated with uncertainty) or probabilistic analysis (performing multiple simulations with probability distributions for each uncertain variable) (FHWA 2012c). A climate-risk-adjusted benefit–cost methodology is presented in Appendix B. This methodology treats multiple uncertainties associated with climate change. Although the recommended approach is more akin to sensitivity analysis, climate risk could also be explored through probabilistic analysis (although such an application could be very resource intensive).

The benefit–cost methodology has two primary purposes within the scope of traditional benefit–cost applications:

- Help agencies weigh potential adaptation strategies in terms of costs and benefits
- Facilitate the evaluation of longer-term adaptation strategies against other types of investments, especially shorter-term projects intended to improve the performance of today's roadway network. This application, which involves direct comparison of benefit–cost ratios, could help align support for adaptation projects amid immediately pressing agency needs.

This approach is intended to supplement, or add an additional dimension to, an agency's existing investment decision-making processes, especially if benefit–cost methods are already in use.

Summary

To most transportation agencies, the most important concern with climate change adaptation will be answering the question of what to do. This chapter has suggested approaches for incorporating climate change considerations into the environmental analysis and project development processes. At some point, transportation agencies will have to start thinking carefully about how project design and development might be affected by changing climatic conditions. Even if an agency does not want to use the design options information found in the spreadsheet and decision support tool on the accompanying CD-ROM (of which Tables I.8 through I.10 and Figures I.13 through I.15 are examples), the thinking process for considering adaptation in its project development process will likely follow the steps presented in this chapter:

1. Review environmental and institutional setting and project requirements
2. Identify the possible climate-affected design parameters for the given asset type
3. Review past climate trends and obtain and/or calculate climate projections
4. Identify the design components affected by changes in climate
5. Determine adaptation options
6. If desired, conduct a scenario-driven benefit–cost analysis.

CHAPTER 7

Other Agency Functions and Activities

Chapter 2 examined the possible linkages between adaptation assessment and transportation planning, and Chapter 6 described how adaptation could be incorporated into the environmental analysis and engineering activities of project development. This chapter examines the relationship between adaptation concerns and core agency activities with emphasis on construction, operations and maintenance, and asset management. In addition, the chapter discusses the need for institutional collaboration among different agencies and jurisdictions as adaptation strategies are developed.

How Could Climate Change and Extreme Weather Events Affect Construction?

As a "field activity," construction is highly subject to weather and climate conditions. Thundershowers, to say nothing of tornados, blizzards, windstorms, wildfires, or hurricanes, can bring construction to a halt and require significant remedial work to restore haul roads, exposed slopes, erosion and sediment controls, etc. before work can resume. The term "construction season" itself denotes the importance of weather on construction activities.

Table I.11 lists common construction activities along with an indication of weather characteristics that might affect these activities. Of course, highway construction is of relatively short duration compared to climate change. In practice, construction planning, cost estimation, and management are strongly focused on continuous feedback and improvement where actual experience on last year's project becomes the template for next year's project. Thus, the effects of "average" climate change will tend to be accommodated within an agency's (industry's) construction planning and management systems, in keeping with the effects listed in Table I.5. It is expected that over time construction programs will adapt through:

- Changes to the windows available for certain weather-sensitive construction activities (e.g., paving) including, in many cases, a lengthening of the construction season
- Changes in working hours or other strategies to protect laborers from heat waves
- Different types of materials and designs being used (this is not a threat though because in most cases there will be time to produce more temperature- and rain-resistant materials)
- Enhanced erosion and sedimentation control plans to address more extreme precipitation events
- Greater precautions in securing loose objects on job sites or new tree plantings that may be affected by stronger winds

Extreme weather events, however, will likely be of great concern to contractors and owner agencies. Construction planning/scheduling/cost-estimating procedures already adjust estimates for the effects of expected seasonal weather events (rain, drought, heat, cold, and wind)

Table I.11. Weather-related events that affect construction activities.

Construction Activity	Heavy Precipitation	Drought	Strong Wind	Lightning	Low Temperature	High Temperature
Clearing and grubbing	●		●	●		
Concrete	●		●	●	●	●
Crew scheduling	●		●	●		●
Drainage	●	●		●		
Embankment construction	●	●	●	●	●	
Erosion and sedimentation	●		●	●		
Excavation	●			●	●	
Fencing	●		●	●	●	
Painting	●		●	●	●	●
Paving	●				●	
Steel work	●		●	●		
Vegetation	●	●	●		●	●

over project duration. These standard adjustments are typically included in bid documents. Standard planning and bid processes also account for "force majeure," "acts of god," "unforeseeable conditions," etc. Given expected changes in "extreme weather," more elaborate risk-sharing agreements may be warranted.

Yet another effect of extreme weather on construction is in the area of response. States might consider including or enhancing "where and when" provisions in standard and specialized contracts so that project contractors can be put to work quickly to supplement maintenance forces in the wake of extreme weather damage to the transportation system.

How Could Climate Change and Extreme Weather Events Affect Operations and Maintenance?

Chapter 4 provided an overview of the potential impacts of different climate stressors on an agency's operations and maintenance activities. The reader is referred to this chapter for information on climate stressor-related potential impacts on operations and maintenance. The following paragraphs simply lay out the general climate-related concerns for operations and maintenance that agency officials should be concerned about.

With respect to operations, transportation agencies are primarily concerned with "making the most effective use of the existing roadway capacity by improving efficiency (throughput, speed, safety), minimizing the service impacts of any disruption (crashes, weather), and providing special emergency services (evacuation). At the same time, maintaining and improving operational conditions has significant safety impacts, related both to roadway physical conditions (traction, visibility) and operating conditions (stop-and-go and tailback collision risks)" (Lockwood 2008). Weather-related events can affect traffic speed, travel time delay, crash risk, road closure, roadway capacity, and speed variation. Transportation officials already know that weather events likes rainfall, fog, blizzards, floods, sleet, snow, and ice are significant disruptors of travel. By some estimates, snow, ice, rain, and fog cause 15 percent of the total delay on the nation's highways—considerably more in some areas. Lockwood estimates that snow and ice control alone costs state DOTs about $2.5 billion annually—almost 40 percent of road operating costs. With the population in coastal areas vulnerable to extreme weather events expected to more than double over the next 20 years, operations strategies that will allow emergency evacuations and emergency response efforts will become even more critical. Even away from the coasts, managing more disruptive weather events is likely to become a more prominent component of agency operations activities.

Climate Change Actions for Michigan DOT's Operations and Maintenance Activities

Michigan is expecting several changes in climate that will affect how the transportation network is operated and maintained, including a change in the level and temperature of the Great Lakes, more snow due to the "lake effect," increased frequency of freeze–thaw cycle, more frequent and more intense storms, and increased and prolonged intense summer temperature extremes. In response, Michigan DOT officials are considering the following strategies:

More Intense Storms

- Design assets that are less affected by the effects of climate change
- Larger hydraulic openings for bridges over waterways
- Heavier and lengthier armoring of river and stream banks and ditches to prevent erosion
- Investigate greater pavement crowns to move runoff off of pavement quicker
- Design additional in-system detention to meter runoff outflow
- Eliminate bridge design elements that could make a bridge scour critical (i.e., piers in the river), spread footings, use more sheet piling left in place
- Design terraced vegetated slopes using a variety of plant species
- Design more robust pavement markings that can be seen during wet/night conditions
- Larger capacity pumps/pumping stations for below-grade freeways to prevent flooding
- Stronger specifications for protection of work under construction
- Stronger specifications that require contractor response plans for work zone affected by high-intensity storms
- Increased deployment and use of roadway weather information stations to effectively plan and respond to winter storms
- Keep motorists informed of hazardous conditions/roadway closures using appropriate technology (changeable message boards, etc.)
- Develop stronger contingency response plans for extraordinary winter storms
- Monitor potential hazard of snow accumulation during a more frequent storm period along barriers and plan for routine removal
- Create an appropriate winter maintenance budget that reflects the cost of responding to numerous and intensive storms in a manner that meets public expectation
- Create a detailed economic model that speaks to the societal costs of delayed or inappropriate response to winter storms
- Emphasize routine maintenance items such as ditch and drainage structure cleanout to avoid failure during an intense rainfall event

- Monitor and clean, as needed, bike lanes, shoulders, and non-motorized trails in vertical curve sag areas
- Ensure all roadside building designs are LEED certified or modified to be energy efficient
- Encourage more night/cooler weather work to prevent damage such as slab curling, premature cracking, loss of air entrainment in concrete pavements, rutting, and flushing in asphalt pavements
- More closely monitor moisture in aggregate piles
- Incorporate materials whose performances are less variable in weather extremes
- Modify vegetation planting periods to ensure optimal growth and survival
- Stronger specifications for dust control and wind erosion
- Stronger strategies for worker safety during extreme heat periods

Hotter Drier Summers

- Design lower maintenance bridge expansion
- Design seed/vegetation mixtures that create a denser, deep-rooted vegetation mat that is more erosion resistant
- Eliminate monoculture roadside vegetation designs that may not survive extended drought periods or invasive species attack
- Make sure vegetation is managed appropriately during drought periods near roadsides that are susceptible to wildfires
- Monitor and be ready to respond quickly to pavement "tenting" due to excessive heat
- Monitor health of vegetation in right-of-way that may be stressed due to extreme weather or invasive/new northerly migrating insect species and remove/replace, as necessary

Source: Johnson (2012).

Lockwood (2008) suggests that changing climatic and weather conditions lead to several operations actions that transportation agencies should consider:

- "Improvements in *surveillance and monitoring* must exploit a range of potential weather-sensing resources—field, mobile, and remote."
- "With improved weather information, the more sophisticated archival data and integration of macro and micro trends will enable regional agencies to *improve prediction* and prepare for long-term trends."
- "This in turn can support the development of effective *decision support technology* with analyses and related research on needed treatment and control approaches."
- "The objective to be pursued would be road operational regimes for *special extreme weather-related strategies* such as evacuation, detour, closings, or limitations based on *preprogrammed routines*, updated with *real-time information* on micro weather and traffic conditions."
- "For such strategies to be fully effective improved *information dissemination* will be essential—both among agencies and with the public, using a variety of media."
- "Finally, *the institutionalization* of the ability to conduct such advanced operations will depend on important changes in *transportation organization* and staff capacity as well as new, more *integrated interagency relationships.*"

With respect to maintenance as commonly practiced, an agency's maintenance forces "own" the highway system, and as illustrated in Chapter 4, "their" system and "their" activities are likely to be subject to different climatic conditions and extreme weather events. In approaching this topic it is important to keep in mind that as the long-term stewards of the highway system, maintenance forces perform thousands of operations large and small every day to preserve and operate the highway network in a safe and efficient manner. Tasks are typically assigned by work order and classified as either demand (response to an immediate problem that has arisen such as a guard rail or road sign that has been hit) or planned maintenance (such as crack sealing of pavement or painting of a bridge). Maintenance management systems are increasingly being used to better allocate agency maintenance resources.

Maintenance activities, characterized as prevention, preparation, and response strategies, could help adaptation to the effects of climate change. Prevention and preparation activities tend to fall within the purview of asset management and planned maintenance, while response activities are those undertaken in reaction to an event. Planned maintenance, for example, would include replacing signs, pavement markings, and safety devices on a periodic schedule; mowing the right-of-way; and protecting against insects or invasive species. These latter two in particular could see climate-induced changes in the future. With generally warmer temperatures, the growing season will likely last longer, perhaps requiring additional resources for maintaining the right-of-way. More rapid plant growth poses a particular threat to rock slopes as plant roots burrow into the rock face leading to a heightened risk of rock falls and landslides. This threat can be managed by a more frequent slope inspection and vegetation maintenance regime. In some cases, warmer temperatures have already led to entirely new animal, insect and vegetation species in road rights-of-way where prior climatic conditions were too harsh (see Chapter 4).

While nothing new to transportation agencies, extreme weather events could become an increasingly important part of highway maintenance activities, whether it is flooding in Vermont, wildfires in Colorado, or snow in Washington, D.C. To prepare for extreme weather events, maintenance organizations must make sure their management systems are robust enough to increase their planned maintenance activities to reduce and be ready for the impacts of climate change on aging infrastructure.

Maintenance organizations tend to operate on a fixed annual budget cycle and typically cannot meet all the emergent demand and life cycle needs of an aging system. For this reason it is important for maintenance management systems to prioritize needs and carefully meter out resources so as to achieve maximum long-term effectiveness. Climate change and the associated increase in extreme weather is an increasingly important factor in this estimation. Consider culverts, a common highway feature typically managed by maintenance units. Many states maintain a culvert inventory, but often only for the larger bores. Culvert failure can be gradual, as evidenced by dips in the overlying embankment, or failure can be catastrophic resulting in sudden loss of integrity with attendant threat to both the traveling public and downstream residents. For the first few decades of their useful life, properly designed culverts require little maintenance beyond clearing the occasional build-up of debris. However, as decades pass, steel and concrete age, watersheds urbanize, and the climate changes, maintenance forces will likely find themselves increasingly busy with demand maintenance.

Increased rainfall intensity and attendant increases in stream flow beyond culvert capacity can cause flows to back up, building hydraulic head and the risk of catastrophic failure. This situation is especially possible for culverts plugged with woody debris, which can be exacerbated by the death of trees caused indirectly by climate change, such as changed micro climate or the migration of invasive pests as their traditional ranges change with climatic condition. Increased urbanization can also contribute to these problems.

As climate change and its multiple effects threaten the viability of culverts, so too do other factors including age, maintenance level, traffic loads, and even regulatory oversight. As increasing financial, regulatory, and demand maintenance factors make it increasingly difficult to inspect and maintain culverts, the increasing risks due to climate change are exacerbated.

The remedy is to provide additional resources for culvert management, repair, and retrofit; however, this is often beyond the capacity of an overcommitted maintenance budget. The cooperation and communication necessary to obtain general permits for culvert work from regulatory agencies is also sometimes lacking. This is especially unfortunate when the costs of preventive maintenance under repair conditions is but a fraction of the costs of replacement under emergency conditions—not to mention the heightened environmental, social, and economic costs involved with failure. Realization of this fact can prompt simple proactive actions such as tying work orders to GIS coordinates so that problem sites can be more easily and systematically identified, mapped, monitored, and treated to prevent failures.

What Role Can Asset Management Play in an Agency's Climate Adaptation Activities?

A transportation asset management (TAM) system is a strategic resource allocation framework that allows transportation organizations to manage the condition and performance of transportation infrastructure cost effectively. Because each transportation agency is different, there is no single asset management system that can be said to characterize every asset management program in the United States. However there are some common characteristics that suggest where climate change considerations could be integrated into such a system. The following definition of transportation asset management is useful as a starting point (FHWA 2012b):

> "Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives."

To the extent that climate change will provide new stresses on individual facilities and to the transportation system as a whole, an asset management system with its life-cycle perspective on asset conditions can be an important tool for agency managers in assessing future challenges. As noted in a working paper on asset management and extreme weather events for the American Association of State Highway and Transportation Officials (AASHTO),

> "One of the important characteristics of TAM as it relates to extreme weather events is the emphasis on life-cycle costs, considering the costs and benefits of an asset over its entire useful life from project inception to asset removal. Thus, any hazard or stressor that affects the future condition and performance of an asset becomes an important consideration in the timing of rehabilitation and replacement. Effective TAM requires a history of good data, including knowledge about the assets, their condition, performance, and other characteristics that relate to the life of the asset and its ability to continue to provide reliable, safe service. The focus on monitoring asset condition, evaluating performance, and data-driven decision making reinforces the relevance of TAM as a platform for mitigating the impacts of extreme weather events on transportation infrastructure." (Meyer et al. 2012b)

This emphasis on life-cycle costs as a foundation for asset management systems is found in the latest federal transportation legislation, MAP-21. MAP-21 requires the U.S. DOT to establish a process for states to develop a risk-based, performance-based asset management plan for preserving and improving the condition of the national highway system. The plan must include at least the following:

- Summary list, including condition, of the state's national highway system pavements and bridges
- Asset management objectives and measures
- Performance gap identification
- Life-cycle cost and risk management analysis
- Financial plan
- Investment strategies

Several of these components could have relevance to climate change–related factors that affect the condition (current or future) of highway assets, e.g., the objectives and measures for asset management, life-cycle cost and risk management, and investment strategies (Aktan and Moon 2009, AbouRizk and Siu 2011).

Asset management systems also rely on periodic data collection on a wide range of data, most importantly on asset condition, and thus serve as an already-established agency process for monitoring what is happening to agency assets. In addition, some of the more sophisticated asset management systems have condition deterioration functions that link expected future asset conditions to such things as traffic volumes and assumed weather conditions, thus providing an opportunity to relate changing climate and weather conditions to individual assets.

Table I.12 shows how climate change considerations and factors can link to some of the more important components of an asset management system. Incorporating climate change considerations into asset management goals and policies is an important initial step in that it directs those using the system to provide adequate attention of potential climate-related issues, or to focus on targeted types of vulnerabilities (e.g., culverts). Inventorying assets can include characteristics of the asset location indicating whether the asset will be particularly vulnerable to changing climate or weather conditions (see Chapter 4). As noted previously, risk appraisal

Table I.12. Climate change monitoring techniques or adaptation strategies for TAM system components.

Asset Management System Component	Monitoring Technique(s)/Adaptation Strategy(s)
Goals and policies	Incorporate climate change considerations into asset management goals and policies; these could be general statements concerning adequate attention of potential issues, or targeted statements at specific types of vulnerabilities (e.g., sea-level rise).
Asset inventory	Map, potentially using GIS, infrastructure assets in vulnerable areas; inventory assets that are susceptible to climate change impacts; collect elevation information as standard practice; use standard data collection systems between districts so that asset information can be compiled statewide.
Condition assessment and performance modeling	Monitor asset condition in conjunction with environmental conditions (e.g., temperature, precipitation, winds) to determine if climate change affects performance; incorporate risk appraisal into performance modeling and assessment; identify high-risk areas and highly vulnerable assets. Use “smart” technologies to monitor the health of infrastructure assets. Also keep electronic records of maintenance activities, including specific location. Keep electronic records of road closures due to flooding.
Alternatives evaluation and program optimization	Include alternatives that use probabilistic design procedures to account for the uncertainties of climate change; possibly apply climate change–related evaluation criteria, smart materials, mitigation strategies, and hazard avoidance approaches.
Short- and long-range plans	Incorporate climate change considerations into activities outlined in short- and long-range plans; incorporate climate change into design guidelines; establish appropriate mitigation strategies and agency responsibilities.
Program implementation	Include appropriate climate change strategies in program implementation; determine if agency is actually achieving its climate change adaptation/monitoring goals.
Performance monitoring	Monitor asset management system to ensure that it is effectively responding to climate change; possibly use climate change–related performance measures; use “triggering” measures to identify when an asset or asset category has reached some critical level.

Source: Meyer et al. (2010).

could be included in asset performance modeling and assessment that will “flag” those assets that might represent high risk to the agency and to the transportation system. Over time, with advancements in the technologies of monitoring infrastructure health, “smart” sensors may be able to be tied into the periodic monitoring of infrastructure assets with the output linked directly to the asset management system database.

If the asset management system is used to identify strategies and actions to be taken given asset condition, then it can be designed to be a decision support system similar to that presented in Chapter 6, which presents options for climate-related adaptation strategies and hazard avoidance approaches. Many transportation agencies are beginning to use their asset management system to develop short- and long-term asset investment plans, programs, or strategies. In states where climate change is expected to present significant challenges, plans for this investment should consider possible future climate change and its impacts over the life of the plan.

Finally, as noted previously, one of the most valuable roles an asset management system could have for an agency is its continuous monitoring of asset performance and condition. This represents a ready-made platform that is already institutionalized in most transportation agencies and would not take significant resources to modify its current structure (as illustrated in Table I.12) to serve as a climate change resource to the agency. Having such a system in place is critical if the agency decides upon undertaking the threshold policy approach described in the climate adaptation framework.

How Should Coordination with Other Organizations and Groups Work When Considering Adaptation Strategies?

Climate change is a dynamic and complex inter-jurisdictional issue that knows no real boundaries. Some adaptation strategies, that is, those that focus on targeted infrastructure assets (such as bridges and culverts), can be led by individual agencies without any real need for widespread organizational collaboration (except for the potential interaction with resource agencies seeking permits or approvals to make changes). However, other types of adaptation strategies, such as those that examine non-transportation actions to protect transportation assets such as river or water channel modifications to mitigate negative impacts on bridges, will likely necessitate collaborative actions with other agencies (in this example, the USACE).

In addition, actions taken by adjacent communities and other jurisdictions—such as how community rainwater is handled or drainage systems are designed—could negatively affect state transportation assets. In such situations, collaborative opportunities should be sought to share information and coordinate actions across DOTs, MPOs, regional planning commissions, localities, and the federal government as well as with utilities, land use, and environmental agencies. Transportation agencies at various levels will need to partner with each other as well as with other governmental and private sector entities to determine the vulnerabilities of their respective assets to the impacts of climate change and to orchestrate mutually reinforcing actions wherever appropriate and possible. Such determinations will require the use of a variety of technical and policy tools that speak to different roles, responsibilities, and areas of expertise among various stakeholders. Transportation agencies might have to establish durable and effective relationships and protocols to maximize the effectiveness of climate change adaptation actions and to minimize the risk of counterproductive or inconsistent plans and actions.

State DOT and Regional Planning Commission Collaboration in Vermont after Hurricane Irene

"After Irene, the RPCs [regional planning commissions] continued to rely on their local knowledge and connections to assist [the Vermont Agency of Transportation] with specific tasks such as mapping and data collection, resource matching, communications, FEMA grants, and technical assistance. While many RPC staff performed these tasks in their own regions, others helped to establish a Regional Coordination Center and provided support at the State Emergency Operations Center. . . . Because of their relationships with road foremen and other key community members and knowledge of the local transportation network, the RPCs were able to identify damage to roads, bridges, culverts, and other assets" (NADO 2012).

For example, within any one geographic area, the street and highway network as well as intermodal connections may be under the jurisdiction of a half dozen or more agencies. It is not difficult to envision adaptation strategies that might be inconsistent or even conflicting. As an example of "looking beyond the right-of-way," adaptation strategies for transportation should be coordinated with adjacent and nearby transportation facility, utilities, and land owners. It may be as obvious as coordinating climate change, event-driven emergency response plans, or formulating stormwater management strategies on an area-wide rather than a facility-by-facility basis. Or, it could involve issues as fundamental as looking at coordinated land-use/transportation adaptation strategies that rely upon shoreline protection methods as opposed to relocating or realigning the infrastructure. In many ways, notwithstanding the need to develop the best of technical tools, it is the institutional/jurisdictional issues that may prove to be the most challenging when it comes to climate change adaptation. Just as transportation agencies cannot fail to be prepared, neither can they implement the full array of actions they must pursue in isolation.

Strategies for collaboration range from project-specific purpose and needs statements to organizational strategies for joint effort such as task forces. Readers are referred to *NCHRP Report 536: From Handshake to Compact* as a reference on the different strategies that can be used to foster collaborative action (Campbell et al. 2006). As noted in this handbook, the benefits of collaboration among transportation agencies (and by extension collaboration among agencies interested in adaptation) include the followings:

- Responding to public needs that require multimodal or multijurisdictional strategies
- Utilizing new technologies to integrate system and traveler information that crosses modal and jurisdictional boundaries
- Coordinating organizational actions to maximize the effectiveness of infrastructure investment and transportation system operational efficiency
- Improving the probability of securing new funding for the region or organization (by expanding the constituency base for the proposal)
- Sharing the costs of a program or policy initiative that a single organization or group could not afford
- Sharing the risks associated with a new undertaking, which, if attempted by a single organization or group, would not likely be pursued
- Preparing for both planned and unexpected events (such as freeway reconstruction and natural disasters) that could disrupt the transportation system

- Developing effective strategies to respond to or implement programs required by legislation that have as their focus multimodal, multijurisdictional, and/or multidisciplinary solutions

The handbook identifies different organizational actions and methods for enhancing collaboration including purpose and needs statements, agreement on language and terms, ad hoc planning and decision structures, task forces/committees, common work/activities program, staff assignment/rotation, staff training, third-party facilitation, memorandum of understanding/agreement, collaboration technology, co-location of staff, and formation of a new organization. It is not likely that all of these strategies would be relevant for a collaborative adaptation program; however, they do represent a range of strategies that can be used to foster multijurisdictional and multiagency cooperation.

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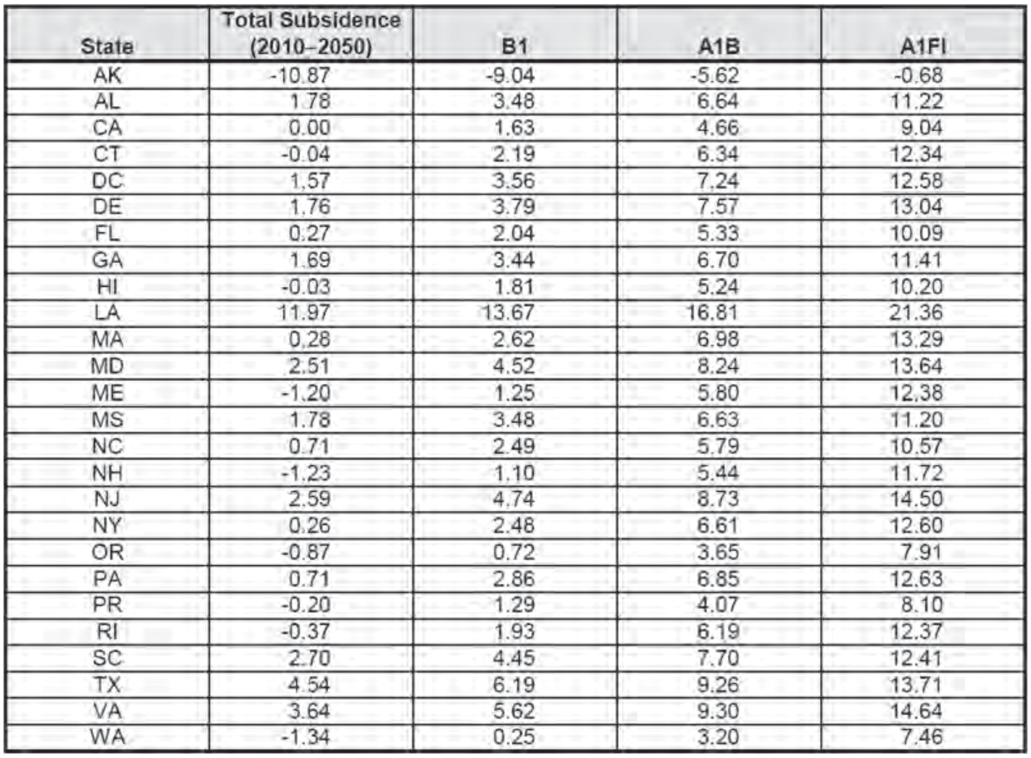
APPENDIX A

Sea-Level Rise Projections

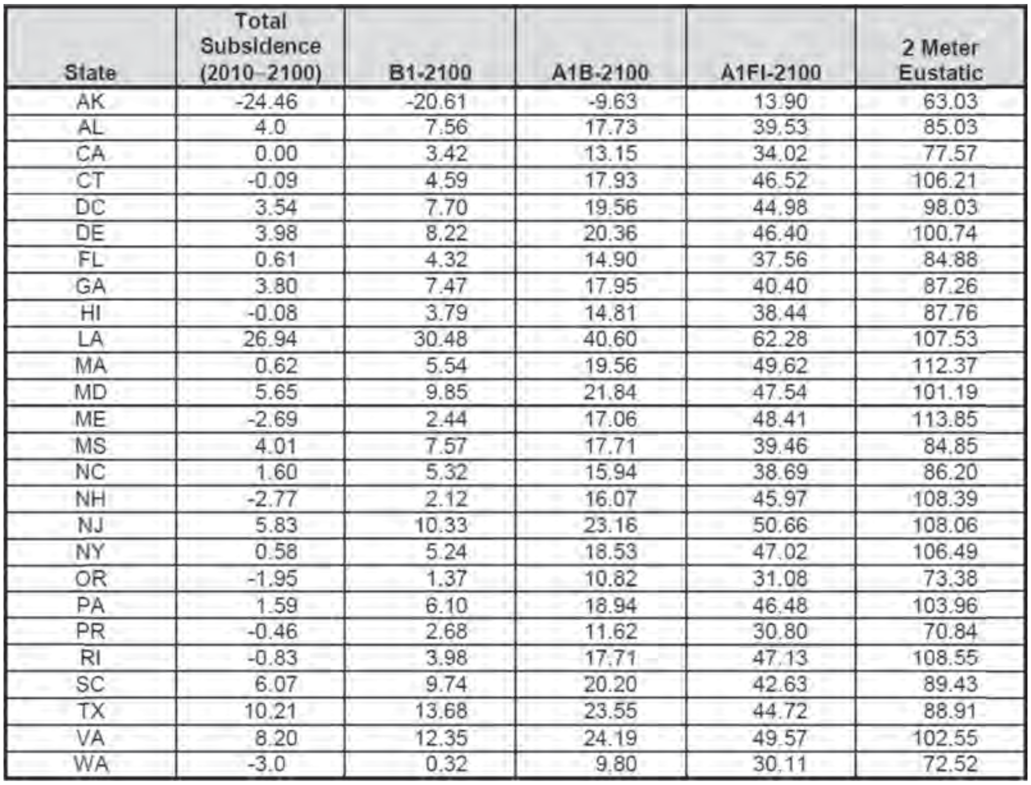
Sea-Level Rise by 2050 Relative to 2010 (in inches taking into account subsidence and uplift)



State	Total Subsidence (2010–2050)	B1	A1B	A1FI
AK	-10.87	-9.04	-5.62	-0.68
AL	1.78	3.48	6.64	11.22
CA	0.00	1.63	4.66	9.04
CT	-0.04	2.19	6.34	12.34
DC	1.57	3.56	7.24	12.58
DE	1.76	3.79	7.57	13.04
FL	0.27	2.04	5.33	10.09
GA	1.69	3.44	6.70	11.41
HI	-0.03	1.81	5.24	10.20
LA	11.97	13.67	16.81	21.36
MA	0.28	2.62	6.98	13.29
MD	2.51	4.52	8.24	13.64
ME	-1.20	1.25	5.80	12.38
MS	1.78	3.48	6.63	11.20
NC	0.71	2.49	5.79	10.57
NH	-1.23	1.10	5.44	11.72
NJ	2.59	4.74	8.73	14.50
NY	0.26	2.48	6.61	12.60
OR	-0.87	0.72	3.65	7.91
PA	0.71	2.86	6.85	12.63
PR	-0.20	1.29	4.07	8.10
RI	-0.37	1.93	6.19	12.37
SC	2.70	4.45	7.70	12.41
TX	4.54	6.19	9.26	13.71
VA	3.64	5.62	9.30	14.64
WA	-1.34	0.25	3.20	7.46

Note: Eustatic sea level rise by 2050 is 1.65 inches for B1, 4.72 inches for A1B, and 9.17 inches for A1FI.

Sea-Level Rise by 2100 Relative to 2010 (in inches taking into account subsidence and uplift)



State	Total Subsidence (2010–2100)	B1-2100	A1B-2100	A1FI-2100	2 Meter Eustatic
AK	-24.46	-20.61	-9.63	13.90	63.03
AL	4.0	7.56	17.73	39.53	85.03
CA	0.00	3.42	13.15	34.02	77.57
CT	-0.09	4.59	17.93	46.52	106.21
DC	3.54	7.70	19.56	44.98	98.03
DE	3.98	8.22	20.36	46.40	100.74
FL	0.61	4.32	14.90	37.56	84.88
GA	3.80	7.47	17.95	40.40	87.26
HI	-0.08	3.79	14.81	38.44	87.76
LA	26.94	30.48	40.60	62.28	107.53
MA	0.62	5.54	19.56	49.62	112.37
MD	5.65	9.85	21.84	47.54	101.19
ME	-2.69	2.44	17.06	48.41	113.85
MS	4.01	7.57	17.71	39.46	84.85
NC	1.60	5.32	15.94	38.69	86.20
NH	-2.77	2.12	16.07	45.97	108.39
NJ	5.83	10.33	23.16	50.66	108.06
NY	0.58	5.24	18.53	47.02	106.49
OR	-1.95	1.37	10.82	31.08	73.38
PA	1.59	6.10	18.94	46.48	103.96
PR	-0.46	2.68	11.62	30.80	70.84
RI	-0.83	3.98	17.71	47.13	108.55
SC	6.07	9.74	20.20	42.63	89.43
TX	10.21	13.68	23.55	44.72	88.91
VA	8.20	12.35	24.19	49.57	102.55
WA	-3.0	0.32	9.80	30.11	72.52

APPENDIX B

Benefit–Cost Methodology for Climate Adaptation Strategies

A benefit–cost (B/C) methodology was formulated to provide results for a "point of decision" analysis—in other words, an exercise to determine whether an adaptation strategy or project is worth the additional expense. However, with minor modifications the approach could be used to guide long-range planning decisions. The accompanying CD to this document includes spreadsheets that can be used to conduct simple B/C analyses based on the methodology described in this appendix. The user provides input values for key variables and the spreadsheet estimates a B/C ratio for the project.

The "point of decision" application is most applicable to two types of situations:

- The current asset is in need of imminent replacement or major reconstruction (i.e., is nearing the end of its life span). The approach can be used to determine whether the incremental costs of adaptation are economically justifiable.
- The current asset is increasingly threatened by climate hazards, meaning that a trigger threshold has been exceeded. Adaptation actions (which range from maintenance, to reconstruction, to abandonment) must be implemented in the immediate future in order to prevent further deterioration of performance. In this case, the approach helps facilitate the selection of appropriate adaptation strategies from a cost-effectiveness perspective.

Note, however, that the B/C methodology could be applied to new facilities or assets where different designs intended to protect the facility from climate change impacts are being considered. In this case, the analysis would consider the incremental costs associated with the different designs and incorporate into the analysis the likelihood of failure given the different designs. If the difference in failure likelihood among the alternative designs is minimal, the analysis in essence becomes one of comparing the benefits of protecting an asset given likely failures due to climate stressors to the costs incurred in providing the protection.

For the "point of decision" methodology, B/C ratios can be considered in each "out" year in order to guide investment implementation. The adaptation strategy that exhibits negative or very low B/C ratios in the near future may return competitive ratios in later years as climate hazards grow more likely and/or the asset condition declines. In other words, the tipping point for cost effectiveness can be established, providing guidance as to the year (or range of years) in which the adaptation strategy should be implemented. This application could also form the basis for the incorporation of climate adaptation strategies into long-range transportation planning documents.

Step-by-Step Climate-Risk-Adjusted Benefit–Cost Methodology

The recommended methodology returns a B/C ratio for an identified adaptation strategy that is weighted by the likelihood of asset failure. In this context, the likelihood of failure is based on a combination of the probability of a climate event occurring and the ability of

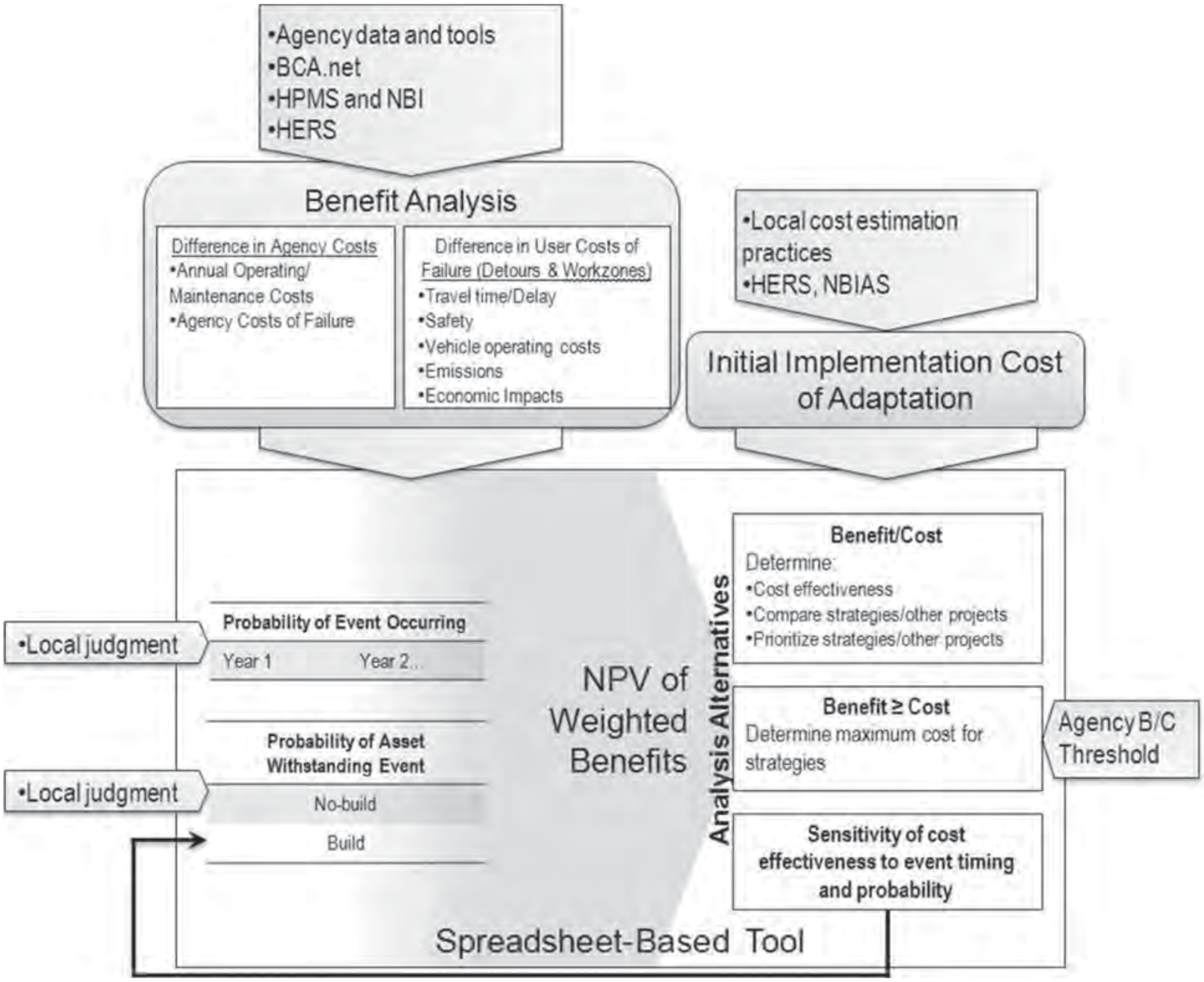


Figure I.B-1. Climate-risk-adjusted benefit–cost methodology.

the infrastructure to withstand the event. This methodology includes a risk assessment that accounts for an asset's current ability to withstand an event, and its ability to withstand it after an adaptation strategy has been implemented.

The recommended approach is intended to allow each agency to apply its own data and customize as necessary. It is illustrated in Figure I.B-1, with further details provided in the following subsections. Arrows illustrate inputs by an agency into the evaluation process.

Step 1. Identify the Highest Risk Infrastructure

Step 1 involves applying the diagnostic framework developed for this research. Thus, by this point in the process those assets considered of greatest risk will have been identified.

Step 2. Estimate Future Operations and Maintenance Costs

The FHWA *Economic Analysis Primer* recommends that the denominator in the B/C calculation represent only the initial cost of a project, and that the change in future agency costs be included in the numerator (FHWA 2012). This step focuses on estimating a portion of the future agency costs associated with operations and maintenance. Additional future costs associated with major rehabilitation or reconstruction work are addressed in Step 3. The *Economic Analysis Primer* also recommends estimating all future costs in constant year dollars, without applying an inflation factor.

Step 2 involves estimating average annual operations and maintenance costs for two scenarios:

- An adaptation scenario, in which the adaptation strategy is implemented
- A no-adaptation scenario, in which the adaptation strategy is not implemented

Ideally, year-by-year estimates of future costs could be developed to reflect the relationship between deteriorating asset conditions, worsening weather conditions, and increasing costs. However, for sketch planning purposes, this level of detail is not required, and an annual average based on historical agency cost records is sufficient. Also note that the relationship between operations and maintenance costs between the adaptation and no-adaptation strategies will vary based on the strategy and climate change being analyzed. For example, if the adaptation strategy is to build a bridge with a deck at a higher elevation, future agency costs will likely be higher for the adaptation scenario than the no-adaptation strategy. However, if the strategy is to use a different pavement design that facilitates increased water drainage, future costs for the no-adaptation strategy (which now must focus on maintaining the drainage area) may be higher.

The outputs from Step 2 are as follows:

OM_A = annual operations and maintenance costs of the adaptation scenario, in current year dollars
OM_{NA} = annual operations and maintenance costs of the no-adaptation scenario, in current year dollars

Step 3. Estimate the Agency Costs of Asset Failure

Step 3 addresses the second component of future agency costs, those associated with an asset failing. In this context "failure" is a relative term that should reflect the adaptation strategy being considered. For example, if the strategy involves raising or strengthening a bridge to withstand higher water levels, failure could be defined as a bridge collapsing. In this example, the agency cost of failure would be the cost of reconstructing the bridge. In contrast, if the strategy involves modifying pavement design to withstand more frequent freeze–thaw cycles, failure could be defined as the point at which pavement requires major rehabilitation.

The output from Step 3 is as follows:

AF = agency costs associated with asset failure, in current year dollars

The agency costs of failure should be estimated independent of the likelihood of failure. This dimension of agency costs will be addressed in later steps.

Step 4. Estimate the User Costs of Asset Failure

Step 4 entails estimating the user costs associated with an asset failing. Again, the term failure is relative to the adaptation strategy being considered. In the example in which failure is a bridge collapse, the costs to the users account for the need to seek an alternative route. These detour costs can include the impacts of travel delay, safety, vehicle operating costs, and other economic impacts resulting from increased travel times. Many agencies have developed approaches for considering the economic implications of transportation projects. These approaches often entail relaying differences in vehicle miles traveled (VMT) and vehicle hours traveled (VHT) to macro-economic indicators such as gross state product and employment. Detours can have a significant impact on both VMT and VHT, which result in increased transportation costs and decreased productivity for local businesses and decreased business attraction for the region. For another perspective on understanding the potential economic impacts of asset failure, refer to Georgia Tech Research Corporation (2012), which covers economic impacts due to the disruption of freight networks.

In the example in which failure is defined as a pavement requiring rehabilitation or reconstruction, the costs to users account for delay experienced during construction. These work zone costs typically address travel delay caused by closing a portion of a roadway or rerouting traffic.

In addition to detour costs and work zone costs, another category of costs that is inherently associated with catastrophic events is the potential, immediate loss of human life associated with the asset failure (this immediate loss of life is different from the loss of life that my occur because of increased travel due to detour routes). However, it can be very difficult to assume the magnitude of these immediate losses. For example, the potential loss of life due to a bridge collapse is a function of several factors including traffic volumes (passing over and under the bridge), time of day, the availability of warning mechanisms (such as posting), and other elements. Furthermore, the environmental changes considered in this research do not always occur suddenly with no warning unlike, for example, earthquakes. Hurricanes and flooding events could be considerable, but come with some warning. In addition, it is assumed that agencies would take the necessary steps such as closing the most vulnerable bridges when a hurricane warning is issued. For these reasons, it is recommended that loss of human life be considered carefully before inclusion in the evaluation of climate adaptation strategies.

When evaluating adaptation strategies, detour costs and work zone costs are the most common costs to consider. However, agencies have flexibility in terms of defining the details regarding which costs to include. For example, if an agency currently evaluates economic impacts of infrastructure projects as part of its B/C methodology, the approach can be included in the adaptation B/C analysis. For agencies not currently using B/C analysis, tools such as BCA.net and resources such as the FHWA *Economic Analysis Primer* can inform the process. Since the details of traditional B/C guidance are addressed in these and other materials, they will not be readdressed as part of this effort.

In traditional B/C analysis, user costs are estimated by year to reflect changes in traffic volumes over time. However, when evaluating climate change adaptation strategies, the timing of an asset failure (and therefore the year in which the user costs are accrued) is variable. Therefore, it is recommended that failure be modeled for a single future year, so that in later steps, the costs can be scaled based on assumed traffic growth rates. This approach requires the following output from Step 4:

UF = user costs associated with asset failure, in current year dollars
Y = year in which user costs have been estimated
$AADT_Y$ = annual average daily traffic (AADT) in year, Y
$AADT_C$ = current AADT

Step 5. Estimate Likelihood of Asset Failure

Step 5 involves estimating the likelihood of asset failure. Asset failure likelihood is composed of the likelihood that the asset will be exposed to a particular climate hazard in a given year and the probability that the asset will withstand the hazard (i.e., the asset's resilience, which may decrease as the asset ages). These components of failure risk are explained below.

- **Risk of climate hazard exposure:** Climate hazard exposure considers the likelihood that a specific climate hazard above the asset's critical threshold may occur in a given out year. For geospatial stressors, like coastal storm surge, this threshold might be expressed in units of increase, such as "2 feet of surge." For first-order stressor types, such as precipitation, the extent to which they contribute to second-order impacts, like flooding, should be considered (e.g., a major culvert is designed for the 1 percent chance flood event, the flow rate of which becomes the critical threshold). Hazards like extreme temperatures, which are likely to affect large geographic swathes despite some local variations, are generally viewed as affecting all assets within a given geography if temperature sensitivity thresholds (e.g., 95°F) are exceeded.

- **Risk of structure failure:** Geospatial climate hazards, such as sea-level rise, for example, may not require a separate failure factor—if indeed sea-level rise causes inundation on a coastal highway, then the simple fact of exposure generally means at least a temporary loss of functionality. For other stressor types, exposure alone does not necessarily signal asset failure (damage, deterioration, or disruption), even if design or material specifications are exceeded. Based on factors such as observed weather-related failures and anticipated future condition data, agency engineers, asset managers, and materials sciences experts must determine a failure probability figure or range.

For instance, in the bridge example, the likelihood of a bridge collapse is a combination of the likelihood that water levels rise and the likelihood that the bridge cannot withstand the higher water levels.

It is important to note that assets can fail in multiple ways because they are subject to multiple climate stressors. For example, bridges over tidal estuaries could fail due to scour from freshwater flooding, scour from saltwater storm surge, excessive wind loads, etc. Each type of event would have its own probability of occurrence. Ideally, the B/C analysis should consider the combined probabilities of all climate stressors and failure scenarios.

The analysis described in later steps is designed to account for temporal differences in the probability of an event. Typically, the probability of an event occurring will increase over time. Therefore, a year-by-year probability of failure is required. The analysis approach also requires a comparison of two probabilities regarding an asset's ability to withstand an event—the probability with the adaptation strategy applied and the probability without. This approach will enable agencies to consider the effectiveness of a proposed strategy.

The following values should be estimated in Step 5:

PE_i = probability of an event occurring in each year i over the time horizon
PW_A = probability that the asset can withstand the event, for the adaptation scenario
PW_{NA} = probability that the asset can withstand the event, for the no-adaptation scenario

Based on these values, the total probability of asset failure can be calculated for the adaptation scenario as follows:

$$PF_{Ai} = PE_i \times (1 - PW_A) \tag{1}$$

where

PF_{Ai} = probability of asset failure in year i, for the adaptation scenario
PE_i = probability of an event occurring in each year i over the time horizon
PW_A = probability that the asset can withstand the event, for the adaptation scenario

A key assumption in calculating the probability of asset failure for the no-adaptation scenario is that if the asset fails, it will be reconstructed with the adaptation strategy deployed. (Note that the approach could also leave the option of replacing in kind, even if it may be subject to failure again, if it makes economic sense to do so). Therefore, if it fails in one year, it would have the same probability of failure for the adaptation scenario in subsequent years. For example, if water levels overtake a bridge that has not been adapted, it is assumed that the new bridge will be built to withstand higher water levels.

In year 1, the probability of asset failure for the no-adaptation scenario can be calculated as follows:

$$PF_{NAi-1} = PE_1 \times (1 - PW_{NA}) \tag{2}$$

where

$PF_{NAi\text{-}1}$ = probability of asset failure in year 1 for the no-adaptation scenario
PE_1 = probability of an event occurring in year 1
PW_{NA} = probability that the asset can withstand the event, for the no-adaptation scenario

In subsequent years, the probability of asset failure for the no-adaptation scenario is a function of the previous year's probability of failure and can be calculated as follows:

$$PF_{NAi} = \{PF_{NA(i-1)} \times PF_{Ai}\} + \{(1 - PF_{NA(i-1)}) \times PE_i \times (1 - PW_{NA})\} \tag{3}$$

where

PF_{NAi} = probability of asset failure in year i for the no-adaptation scenario
$PF_{NA(i-1)}$ = probability of asset failure in the previous year (i.e., year $i - 1$), for the no-adaptation scenario
PE_i = probability of an event occurring in each year i over the time horizon
PF_{Ai} = probability of asset failure in year i for the adaptation scenario (from Eq. 1)
PW_{NA} = probability that the asset can withstand the event, for the no-adaptation scenario

Step 6. Calculate Agency Benefits of the Strategy

Step 6 entails calculating the total agency benefits of the adaptation strategy based on the output from Steps 2, 3 and 5. Annual agency benefits can be calculated as follows:

$$AB_i = AC_{NAi} - AC_{Ai} \tag{4}$$

where

AB_i = agency benefits in year i
AC_{NAi} = agency costs of the no-adaptation scenario in year i (from Eq. 5)
AC_{Ai} = agency costs of the adaptation scenario in year i (from Eq. 6)

$$AC_{NAi} = OM_{NA} + (AF \times PF_{NAi}) \tag{5}$$

where

AC_{NAi} = agency costs of the no-adaptation scenario in year i
OM_{NA} = annual operations and maintenance costs of the no-adaptation scenario (from Step 2)
AF = agency costs associated with asset failure (from Step 3)
PF_{NAi} = probability of asset failure in year i for the no-adaptation scenario (from Eq. 3)

$$AC_{Ai} = OM_A + (AF \times PF_{Ai}) \tag{6}$$

where

AC_{Ai} = agency costs of adaptation scenario in year i
OM_A = annual operations and maintenance costs of the adaptation scenario (from Step 2)
PF_{Ai} = probability of asset failure in year i for the adaptation scenario (from Eq. 1)

Step 7. Calculate User Benefits of the Strategy

Step 7 calculates the total user benefits of the adaptation strategy based on the output from Steps 4 and 5. Total user benefits can be estimated by calculating the user benefits in each year (user benefits will increase over time as traffic volumes increase) and converting the results to a net present value. Annual user benefits can be calculated as follows:

$$UB_i = UC_{NAi} - UC_{Ai} \tag{7}$$

where

UB_i = user benefits in year i
UC_{NAi} = user costs of the no-adaptation scenario in year i (from Eq. 8)
UC_{Ai} = user costs of the adaptation scenario in year i (from Eq. 9)
$UC_{NAi} = UF \times PB_{NAi}$

$$UC_{NAi} = UF \times PF_{NAi} \tag{8}$$

where

UC_{NAi} = user costs of the no-adaptation scenario in year i
UF = user costs associated with asset failure (from Step 4)
PF_{NAi} = probability of asset failure in year i for the no-adaptation scenario (from Eq. 3)

$$UC_{Ai} = UF \times PF_{Ai} \tag{9}$$

where

UC_{Ai} = user costs of the adaptation scenario in year i
UF = user costs associated with asset failure (from Step 4)
PF_{Ai} = probability of asset failure in year i for the adaptation scenario (from Eq. 1)

Step 8. Evaluate Results

There are three options for using the benefits calculated in Step 6.

A. Calculate a Benefit–Cost Ratio

Estimate the initial cost of the adaptation strategy and calculate a B/C ratio as follows:

$$BCR = \frac{\sum(AB_i \times D_i) + \sum(UB_i \times D_i)}{C} \tag{10}$$

where

BCR = B/C ratio of strategy
AB_i = agency benefits in year i (from Eq. 4)

D_i = discount factor for year i [for guidance on estimating a discount rate, refer to FHWA (2012)]
UB_i = user benefits in year i (from Eq. 7)
C = initial cost of the adaptation strategy

The results can be used for the following purposes:

- Determine if a potential adaptation strategy is cost effective (e.g., if the B/C ratio is greater than or equal to 1)
- Compare multiple potential adaptation mitigation strategies (e.g., rank by decreasing B/C ratio)
- Compare a potential adaptation strategy against another potential project, such as a capacity expansion project or a non-transportation adaptation strategy (e.g., compare the incremental B/C ratio from each potential project from the lowest to highest cost project)

B. Determine a Minimum Benefit–Cost Ratio, above which a potential strategy becomes cost effective

For example, the threshold could be set to 1.0 or 1.5. This threshold and the benefits calculated in Steps 6 and 7 could be used to calculate a maximum cost of a cost-effective adaptation strategy. This cost could serve as an initial filter for evaluating a range of potential strategies, or as guidance for site-specific design work. Note that if this approach is used, the assumptions regarding the future operations and maintenance costs and the probability of the adapted asset to withstand an event should be reevaluated once a specific strategy has been identified.

C. Conduct a Sensitivity Analysis Based on the Probability and Timing of an Event Occurring

Year-by-year event probabilities were established in Step 5. Changing these assumptions would enable agencies to explore the climate change characteristics that affect when a potential strategy becomes cost effective. For example, what if there is a 10 percent chance of the event occurring after 30 years? What if, instead, there is a 20 percent chance of it occurring after 30 years?

Implementation Issues

The methodology described in the previous section is not intended to replace the agency decision-making process, but simply to inform it with an assessment of the benefits of different strategies relative to each other or to doing nothing. There are other qualitative and quantitative considerations that could be incorporated into the project prioritization process.

Additional issues to be considered during implementation include the following:

- There are aspects of this approach that require a time commitment from the agency performing the analysis. Since each climate phenomenon, potential impact, existing infrastructure conditions, and potential transportation and economic impacts of failure are site specific (both between regions and even within a region), any analysis using the foregoing methodology should use site-specific data and inputs as much as possible. Also, in order to get the best possible data for analysis, the preferred methodology assumes that an agency is capable of modeling travel delay and can estimate operating and maintenance costs of different strategies.
- Agencies can choose to calculate either traditional or incremental benefits and costs. In a traditional approach, two alternatives are considered—the build and the no-build scenarios. In an incremental approach, both alternatives involve some work, such as replacing a bridge versus replacing it at a higher elevation to account for potential increases in water levels. This second alternative will have costs and benefits that are incremental to those of the

first. Incremental calculations are recommended. Since they compare the marginal costs of adaptation strategies relative to costs for standard, planned improvements and upgrades to infrastructure, they will likely fair better in terms of overall cost effectiveness.

- The recommended analysis can be performed for a single adaptation project (e.g., strengthen an existing bridge) or a collection of projects (e.g., a program aimed at strengthening several bridges). However, the benefits calculations may get complicated as the number of projects increases, and care should be taken to be consistent in the calculations regardless of the number of projects being considered. This will ensure that the results of the analysis can be compared against each other and against project-level B/C ratios for other potential transportation projects.

Illustrative Example

This section illustrates the application of the process described previously, focusing on a bridge reconstruction project. The adaptation strategy being considered includes raising and strengthening a bridge so that it can withstand higher water levels. The bridge is being considered for reconstruction regardless of whether the adaptation strategy is implemented. The following key assumptions for Steps 2, 3, 4, 5, and 8 were made. (Steps 6 and 7 involve the mathematical combination of the estimates in Steps 4 and 5 and are therefore not shown in this example.)

Future Operations and Maintenance Costs (Step 2)

The agency estimated that there are no significant differences in annual operation and maintenance costs between the two scenarios (reconstructing the bridge with the adaptation strategy and reconstructing it without the strategy). Therefore, for the purposes of the cost-effectiveness analysis, future operations and maintenance costs were not considered. Since the costs are equal for the two scenarios, they would cancel each other out in subsequent calculations.

Agency Costs of Failure (Step 3)

If the bridge collapses, it will be reconstructed with the adaptation strategy implemented. The agency has estimated the cost of that action to be $170 million, which is $144 per square foot of deck area.

User Costs of Failure (Step 4)

The agency has considered travel time costs, fuel costs, and economic costs (which were estimated as a loss in productivity due to the first two costs) associated with detour length. If the bridge fails, users will be required to seek an alternative route. The user costs were based on the following bridge characteristics and assumptions:

- Current AADT = 35,000
- Future AADT (year 2050) = 65,000
- Percentage of trucks = 12
- Detour length = 5 miles
- Detour travel time = 10 minutes
- Project development and construction time (length of detour) = 2 years
- Value of auto time = $13.75 per hour
- Value of truck time = $72.65 per hour
- Average fuel consumption = 18 miles per gallon
- Average fuel costs = $3.85 per gallon

Based on these assumptions, the annual user costs of failure ranged from $130 million in 2011 to $234 million in 2050 (these values are in constant year dollars).

Likelihood of Asset Failure (Step 5)

The agency estimated the following probabilities related to the likelihood of the bridge failing:

- **Probability of the event occurring.** The agency determined that a 100,000 cubic feet per second (cfs) flood event would fail the bridge. The 100,000 cfs event was defined under current climate conditions as a 500-year or 0.2 percent chance storm event. Based on the probability, the agency has an estimated risk of 2.0 percent of the failure threshold being exceeded from 2010 through 2020. The agency estimates that flows after 2020 will increase by 2 percent per year from 2020 through 2040, raising the probability of a 100,000 cfs event from 0.2 percent (500-year) to 1.0 percent (100-year). The incurred probability of exceedance of the 100,000 cfs event under this scenario increases from 2 percent during the 2010 decade to 4 percent during the 2020 decade, and up to 8 percent during the 2030 decade. (Agencies have the option to choose later horizon years as climate hazards grow more likely and/or the asset condition declines).
- **Probability of withstanding the event.** Failure was defined as “the bridge requiring reconstruction.” The agency has estimated that in the no-adaptation scenario, the bridge would have a 30 percent chance of withstanding the event, and that in the adaptation scenario, it would have a 99 percent chance.

Results (Step 8)

The agency estimated the initial cost of the adaptation strategy as the incremental cost between reconstructing the bridge without the adaptation strategy ($148 million) and reconstructing it with the strategy ($170 million). The initial cost of the strategy was thus estimated to be $22 million.

Based on this initial cost, the estimates for the agency costs of failure and the user costs of failure described above, and an annual discount rate of 4 percent, the agency calculated a B/C ratio greater than 7. This result indicates that the proposed adaptation strategy from an economic analysis perspective is a worthwhile expenditure of funds (i.e., the B/C ratio is greater than 1).

The agency also repeated the calculation assuming the full initial cost of $170 million to see if the adaptation strategy would make economic sense if the bridge were not slated for reconstruction already. The resulting B/C ratio was 0.96. This result indicates that although the adaptation strategy is approaching a regional threshold for worthwhile expenditure, there are likely other potential projects with greater B/C ratios. Therefore, the opportunity cost associated with this strategy (i.e., the inability to implement another more cost-effective project) is likely too high to warrant its implementation.

Incorporating Climate-Risk-Adjusted Benefit–Cost Results into Infrastructure Decision Making

Generally, B/C analysis is intended to support agencies in identifying and valuing the direct and indirect benefits and costs of projects over a multiyear time frame. B/C analysis is intended to help agencies direct scarce resources to the most beneficial projects and to provide transparency in decision making.

As with traditional B/C approaches, climate-risk–adjusted analyses can provide key inputs into several different transportation decision-making processes, including:

- Long-range planning: With minor modifications, the B/C methodology can be employed to help agencies identify the appropriate time frames in which implementation of adaptation strategies is cost effective (this is the "planning" application type).
- Project selection (programming): If economic analysis is used as part of a project selection/prioritization process [for creation of the transportation improvement plan (TIP)/state transportation improvement plan (STIP), for example], this approach can be used to compare the benefits of an adaptation project (or a project incorporating adaptation alternatives) to all other project types (this application is of the "point of decision" type).
- Project development: After a major project is programmed (included in a TIP or STIP, for example), it may need to undergo an alternatives analysis. Climate risk can be examined to inform the selection of the preferred alternative (this use is consistent with the "point of decision" application type).

Many states and metropolitan planning organizations already use economic tools including B/C analysis to help them determine the most beneficial projects by identifying, quantifying, and valuing benefits and costs over a multiyear time frame. The diagnostic framework in this report suggests that by incorporating climate risk into the use of B/C analysis, agencies can determine what adaptation strategies are the best investment in addressing climate change impacts to highway facilities and services.

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PART II

Research Report

SUMMARY

Climate Change, Extreme Weather Events, and the Highway System: Research Report

This report presents the findings of a research project that explored the potential impacts of climate change and extreme weather on the U.S. highway system. A conceptual framework of the highway network consisting of a road segment, corridor, and network was developed to illustrate how climate change could affect the road system. There are five key components to the design of a typical road segment—subsurface/foundation conditions, materials specifications, structures, typical cross sections, and drainage/erosion—that could be affected by some change in environmental conditions such as precipitation, temperature, and wind. Design standards, guidelines, and standard operating procedures have been in place in many transportation agencies for many years and most of these procedures, etc. were based on historical records of environmental conditions. As conditions change, it is likely that some of these procedures will have to change as well to reflect new circumstances and environmental stressors.

At the corridor level, the potential impacts of changing environmental conditions due to climate change on a typical road segment would accumulate over a corridor and throughout the network where similar circumstances exist. In addition, corridor-level concerns with changing environmental conditions will likely relate to outside-of-right-of-way environmental mitigation; erosion, drainage, and runoff impacts; right-of-way maintenance; and construction practices and activities. For example, changes in temperature and precipitation and the corresponding need to utilize different construction materials could affect construction practice. A lengthening or shortening of the construction season could also influence a transportation agency's construction program.

The network-level focus relates to the overall management of the highway network, including building and protecting the agency's assets from climate stressors as well as developing system management strategies for expected disruptions. Specific climate change-related concerns at the network level relate to alternate routes and corresponding system operations strategies; the connection to intermodal facilities; location engineering (where to put the facility to begin with); and protecting building and other agency assets.

In examining the future U.S. socio-demographic context for climate change, the report concludes that:

- The U.S. population will continue to grow with most of this growth occurring in urban areas and in parts of the country expecting notable changes in climate.
- The composition of this population will be very different than it is today, with more diverse populations and elderly in the nation's population mix.
- Significant levels of housing and corresponding development will be necessary to provide places to live and work for this population, with much of this development likely to occur in areas subject to changing environmental conditions.

- Increasing population growth will create new demands for transportation infrastructure and services, once again in areas that are vulnerable to changing climate conditions.
- The nation's highway system will be facing increasing demands for reconstruction and rehabilitation over the next 40 years (to 2050), which provides an opportunity to incorporate climate adaptation strategies into such efforts, if appropriate.

The research used climate change models to project future climate conditions. The models showed that temperatures in the lower 48 states are projected to increase about 2.3°C (4.1°F) by 2050 relative to 2010. While all U.S. regions are projected to increase in temperature, the amounts will vary by location and season. In general, areas farther inland will warm more than coastal areas, because the relatively cooler oceans will moderate the warming over coastal regions. In addition, northern areas will warm more than southern areas because there will be less high-latitude snow cover to reflect sunlight. More warming is projected for northern and interior regions in the lower 48 states than for coastal and southern regions.

In general, the models project, and observations also show, that the Northeast and Midwest are likely to become wetter while the Southwest is likely to become drier. In addition, all the climate models project an increase in precipitation in Alaska. It is not known whether precipitation will increase in other areas such as the Northwest or the Southeast. While the models tend to show a drier Southwest and a wetter Northeast and Midwest, the differences across the models mean it is not possible to forecast exactly which localities become wetter or drier nor where the transitions between wet and dry areas lie. Climate models tend to project relatively wetter winters and drier summers across most of the United States. However, this does not mean that all areas are projected to receive more precipitation in the winter and less precipitation in the summer. The models also project a larger increase in summer temperature than winter temperature.

Extreme temperatures will get higher. This means that all locations will see increases in the frequency and duration of occurrence of what are now considered extreme temperatures such as days above 32°C (90°F) or 35°C (95°F). In the long run, the number of days below freezing will decrease in many areas, particularly southern locations.

Precipitation intensities (both daily and 5-day) are projected to increase almost everywhere, although the largest increases tend to happen in more northern latitudes. Recent research has suggested that there could be fewer hurricanes, but the ones that do occur, particularly the most powerful ones, will be even stronger.

Global sea levels are rising. Projections of future sea-level rise vary widely. The Intergovernmental Panel on Climate Change (IPCC) projects that the sea level will rise 8 inches to 2 feet (0.2 to 0.6 meter) by 2100 relative to 1990. Several studies published since the IPCC Fourth Assessment Report, however, estimate that sea levels could rise 5 to 6.5 feet (1.5 to 2 meters) by 2100. Sea-level rise seen at specific coastal locations can vary considerably from place to place and from the global mean rise because of differences in ocean temperatures, salinity, and currents and because of the subsidence or uplift of the coast itself.

A diagnostic framework was developed that provides highway agency staff with a general step-by-step approach for assessing climate change impacts and deciding on a course of action. The framework, which can be applied at the systems planning level down to the scale of individual projects, consists of:

Step 1: Identify key goals and performance measures for the adaptation planning effort.
Step 2: Define policies on assets, asset types, or locations that will receive adaptation consideration.
Step 3: Identify climate changes and effects on local environmental conditions.
Step 4: Identify the vulnerabilities of asset(s) to changing environmental conditions.

Step 5: Conduct risk appraisal of asset(s) given vulnerabilities.
Step 6: Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness, and defensibility of options.
Step 7: Coordinate agency functions for adaptation program implementation (and optionally identify agency/public risk tolerance and set trigger thresholds).
Step 8: Conduct site analysis or modify design standards (using engineering judgment), operating strategies, maintenance strategies, construction practices, etc.

This eight-step process is inherently a multidisciplinary and collaborative one. It is not likely that a state transportation agency has internal staff capability on climate science. In most cases, these agencies have been working with the local university or the state climatologist in order to obtain such input. In many cases, the vulnerability and risk assessment process depends on local input on what is considered to be the most critical assets in an urban area. Importantly, the actions taken by local communities and governments, such as land use approval and street/drainage design, could have significant impact on the ability of state assets to handle larger loads, and thus the need for coordination.

A range of impacts on the highway system can be anticipated from different climate stressors. These impacts include both impacts to the infrastructure itself (and thus how facilities are designed and constructed) and to operations and maintenance. In addition to the direct effects of climate changes on highways, climate change will affect ecological dynamics in ways that will have implications for transportation systems. The strategies for dealing with climate change and extreme weather events will differ by functional activity within a transportation agency. For example, climate change adaptation can be considered in planning, environmental analysis, design, infrastructure retrofit, construction, operations, maintenance, emergency response, and public outreach and communications. Each activity will usually require different analysis approaches, data, and resulting strategies.

Of particular interest, as agencies increasingly adopt transportation asset management (TAM) approaches, opportunities will exist to integrate consideration of weather risk and climate change into TAM objectives, data collection, performance measurement, monitoring, and resource allocation decisions. Over time, the integration of weather and climate information into TAM will help agencies make targeted investments or allocation decisions that will increase the resilience of the network and of individual assets to changing environmental conditions.

Most agencies that are concerned about adaptation begin by conducting a risk assessment of existing assets. Most of these risk assessments remain largely qualitative and based on professional judgment. Climate-related risk is more broadly defined in that risk can relate to impacts beyond simply the failure of the asset. It relates to the failure of that asset in addition to the consequences or magnitudes of costs associated with that failure. In this case, a consequence might be the direct replacement costs of the asset, direct and indirect costs to asset users, and, even more broadly, the economic costs to society given the disruption to transportation caused by failure of the asset or even temporary loss of its services (e.g., a road is unusable when it is under water). An integrated risk assessment is performed on vulnerable assets with the assessment considering the likelihood of impacts and their consequences. These two factors are related to each other and their intersection determines the risk level facing an asset. Adaptation options can then be considered for high- or medium-risk assets while low-risk assets are given lower priority.

Most studies have adopted a qualitative assessment of the risks associated with specific transportation assets. Although the definition of risk includes some indication of probable occurrence, in reality, such probabilities are hard to formulate, especially when considering that the occurrence in question might not be real until many years into the future. To account for this uncertainty, most studies have relied on qualitative or subjective assignment of risk. Thus, "high," "medium," or "low" is often used to indicate the level of risk associated with individual assets. Even those approaches considered more quantifiable use ordinal rankings of values, that is, "1," "2," or "3" to indicate relative risk. The intent of these approaches is straightforward—to provide decision makers with some sense of where investment in the transportation system would provide the greatest reduction in risk associated with climate change-related disruptions.

Few agencies have gone to the point of systematically inventorying their assets to identify how each transportation link or facility will be affected by climate change. Nonetheless, as some states have finished their initial efforts at adaptation planning, some have begun the process of identifying vulnerabilities to their transportation infrastructure in a more comprehensive manner.

There is a growing understanding among researchers and highway officials that climate change and extreme weather events are a threat to many aspects of the highway system, which warrants spending resources to investigate the specific risks they pose. Both domestically and internationally, however, limited action has been taken "on the ground" to build resiliency into the transportation system. Indeed, with some notable exceptions, much adaptation work remains at a planning or risk assessment level and has yet to be incorporated into the design of individual projects. This is likely to change in the near future as the risk assessment studies progress and as transportation officials begin to realize that in certain areas a changing climate could have significant impact on highway planning, design, construction, and operations/maintenance.

Although some question the projections of future climate conditions, most agree that the United States has experienced record extreme weather events over the past several years. The frequency and severity of such events have seemed to increase; infrastructure damage and community costs have risen; the impact of recovery costs on maintenance budgets and on regular operations activities continues to become more significant; and perhaps, most importantly, public expectations of a transportation agency's ability to recover the transportation system quickly and efficiently have increased greatly. In several instances, the recurring pressures on state transportation officials to prepare for, manage, and recover from extreme weather events have caused organizational change, development of new management responsibilities (e.g., emergency management officials), modification of standard operating procedures, and staff training in managing and administering recover efforts. This report recommends steps that can be taken by transportation agencies to prepare for extreme weather events, manage agency operations during the event, and conduct post-recovery operations.

The final section of the report offers 27 suggestions for further research and information dissemination. These recommendations are categorized into five major topics: planning; project development; construction, operations, and maintenance; system management and monitoring; and an "other" category that focuses on institutional capacity building.

CHAPTER 1

Introduction and Research Objectives

1.1 Introduction

Climate change has received increasing attention worldwide as potentially one of the greatest challenges facing modern society. This attention has focused particularly on two topics. First (and the one receiving the most attention), how can greenhouse gas (GHG) emissions be reduced to decrease the rate and threat of climate change? Second, how can a future world be prepared for changing climatic conditions that are likely even if the pace and magnitude of the level of emissions entering the atmosphere are successfully reduced?

Over time, sea-level rise threatens to permanently inundate low-lying communities and their transportation facilities such as coastal highways and ports (Suarez et al. 2005). Increased risk of coastal flooding in conjunction with sea-level rise, however, may pose a more serious risk than inundation alone. Climate change science suggests that the intensity of storms, particularly the most powerful hurricanes, will increase in the future. This means stronger winds and higher storm surges—on top of higher sea levels, which will put even more land and transportation facilities at risk. Very high temperatures can cause concrete pavements to buckle and can soften asphalt roads, leading to rutting and subsidence. High temperatures will cause more precipitation to fall as rain rather than snow, which may reduce transportation disruptions, but increase drainage problems. The melting of the permafrost will create significant challenges to road design and maintenance (as is happening in Alaska). Increased frequency of freeze–thaw cycles could significantly affect pavement designs. Precipitation patterns and intensity could change dramatically, affecting transportation networks and facility operations. Some areas may face increased precipitation and increased flooding. For example, climate models tend to project increased winter precipitation in the Midwest and Northeast, increasing the risk of early spring flooding as snow packs melt. Precipitation intensity is projected to increase even more in the future, increasing the risk of flooding, particularly from convective thunderstorms in the summer.

Extreme weather events are symptomatic of the type of weather many climate scientists believe will be seen more in the future, and which will significantly impact state departments of transportation (DOT) operations. The year 2012 set a record for extreme weather events, with 3,527 monthly weather records broken for heat, rain, and snow in the United States, according to information from the National Climatic Data Center (NOAA 2013). The National Resources Defense Council's (NRDC) website on extreme weather noted the hottest March on record in the contiguous United States, and July was the hottest single month ever recorded in the lower 48 states (NRDC 2013). The United States experienced the worst drought in 50 years across the nation's Midwest and South, with over 1,300 U.S. counties across 29 states declared drought disaster areas. Wildfires burned over 9.2 million acres, with the average size of the fires setting an all-time record of 165 acres per fire. Hurricane Sandy's storm surge height (13.88 feet) broke the all-time record in New York Harbor and brought record devastation across New Jersey and New York with floodwaters and winds.

A sampling of states from the NRDC website gives a sense of the magnitude of extreme weather events:

California: A total of 37 broken heat records, 5 broken snow records, 53 broken precipitation records, and 102 large wildfires
Kansas: A total of 64 broken heat records, 42 broken precipitation records, and 30 large wildfires
Montana: A total of 59 broken heat records, 16 broken snow records, 17 broken precipitation records, and 128 large wildfires
Texas: A total of 144 broken heat records, 8 broken snow records, 115 broken precipitation records, and 34 large wildfires

In addition to the direct effects on road infrastructure, changing climate conditions can affect many of the ecological functions of lands surrounding roads, and possibly influence existing wetland and habitat banks and environmental mitigation strategies that are commonly considered today by state transportation agencies as part of the project development process. Thus, future highway projects might face very different environmental mitigation requirements than they do today.

An ever-increasing number of state and local officials have begun to examine how activities in their jurisdiction could be affected by changes in such environmental conditions. In almost all of these efforts, the transportation system has been identified as one of the most important sectors that could face significant impacts of a changing climate and of extreme weather events. The basic premise of road design is that the physical form and materials specifications associated with the design itself must reflect the environmental conditions within which the facility is constructed. Operational and maintenance strategies must relate to the "external" conditions that affect system performance. The highway project development process must take into consideration likely impacts on environmental resources resulting from the combined effect of changing climatic conditions and the associated changes in the physical and operational characteristics of infrastructure that will be required.

A strategic perspective and specific guidance are needed on how the transportation sector can best prepare for likely changes in environmental conditions over the next half century. Many, for example, are interested in incorporating climate change considerations in a strategic asset management system that provides a systematic approach to changing some elements of infrastructure characteristics at the appropriate time. By starting early, and by integrating the strategies and actions needed to address anticipated effects of climate change as part of an ongoing process of infrastructure preservation and asset management, and by doing this over a period of decades, the transportation community can be prepared for these impacts. And it will have to be done in a way that is affordable, avoiding the far more costly approaches of responding to short-term "crash programs" or, even worse, the need to rebuild facilities that suffer sudden and potentially catastrophic damage as a result of extreme weather events.

At the same time, the transportation sector cannot afford to over-invest in climate adaptation. With limited budgets and a large backlog of infrastructure needs, transportation agencies will need to use the most cost-effective strategies, from retrofitting existing infrastructure to strengthening design standards for new infrastructure. A flexible framework for guiding the timing and sequence of climate adaptation investments is needed.

1.2 Problem Statement and Research Objectives

The goal of this research was to provide insights, guidance, and tools to mitigate the risks of climate change impacts on the nation's highway systems and related intermodal facilities. The objectives were to (1) synthesize the current state of knowledge on the range of impacts of climate change on the highway system by region of the United States for the period 2030–2050; (2) recommend institutional arrangements, tools, approaches, and strategies that state DOTs can use during the different stages of planning and project development and system management to adapt both infrastructure and operations to these impacts; (3) prepare guidance, materials, and methods for dealing with these impacts; and (4) identify future research and activities needed to improve understanding of possible impacts and the steps needed for adaptive system management. Note that Part I of this volume, the Practitioner's Guide, accomplishes the third objective.

1.3 Study Scope and Research Approach

This study examined potential climate change impacts on the U.S. highway system. Although there are references to impacts and studies on other parts of the nation's transportation system, the study focuses on highways. In many ways, however, the results of this research can be used by those responsible for non-highway modal operations. For example, impacts and adaptation strategies for pavements would be of interest to those responsible for airport and transit paved surfaces. Drainage and temperature stresses are common to all transportation modes, and thus the information provided in this report would be of interest to those concerned with such issues. The diagnostic framework for adaptation planning presented in this report is also defined in such a way as to provide guidance to those interested in any mode of transportation.

An important boundary of this analysis was the projection of climate impacts and identification of potential adaptation strategies to the target year of 2050. It is understandable that 2050 was chosen by the oversight panel as the target year given a desire to produce research results that can be used by transportation officials today. However, climate modeling suggests that the major climate change-related impacts to the transportation system are not likely to occur until the latter part of the century. The major exception to this are extreme weather events, which in recent years have focused attention on the record precipitation, heat, and dangerous storms being experienced in all parts of the country. The target year of 2050 was maintained in the research, except in one case, sea-level rise. The research team felt that the rise in sea level over the next 40 years was not likely to cause that significant a challenge in most coastal parts of the country. Thus, projections of sea-level rise were provided for both years 2050 and 2100.

It is interesting to note that much of the literature and concern relating to climate change seems to be centered on coastal impacts, primarily from sea-level rise combined with storm surge. Clearly, such impacts are significant and deserving of attention. However, this study describes other impacts relating to drought, wildfires, dust, wind, and heavy storms that will likely affect non-coastal states. Climate change and extreme weather events are not just a concern for coastal communities. This report adopts this wider perspective on both the impacts and potential adaptation strategies.

The report provides numerous references on adaptation efforts throughout the world, with emphasis given to the United States. However, except in several instances (and once again primarily focused on water and precipitation impacts), much of the progress in adaptation planning has occurred overseas in countries such as Australia, Sweden, and the United Kingdom. The scope of the literature review and references to specific adaptation-related topics thus includes numerous examples from other countries.

The literature on transportation adaptation planning is rapidly expanding, especially in response to federally funded pilot projects that aim to highlight the characteristics and key factors associated with climate adaptation studies. Those interested in adaptation planning should keep track of developments from the Federal Highway Administration (FHWA) and the Federal Transit Administration (FTA) of the U.S. DOT, both of which have funded important pilot studies on adaptation of the transportation system to a changing climate. The U.S. DOT has a climate change clearinghouse (http://climate.dot.gov/) as do groups such as the American Association of State Highway and Transportation Officials (AASHTO; http://climatechange.transportation.org/), Georgetown University Climate Resource Center (http://www.georgetownclimate.org/resources/transportation-and-climate-change-resource-center), the Center for Climate and Energy Solutions (http://www.c2es.org/), and many others.

The research design for this project consisted of an extensive literature review and the use of case studies to test the methods and approaches developed. For example, the diagnostic framework that serves as the foundation for the study analysis was tested in three states—Michigan, North Carolina, and Washington. The benefit–cost methodology presented in Appendix B of Part I, the Practitioner's Guide, was based on project data obtained from these three states as well. In addition, this research benefited from parallel work sponsored by the FHWA in the Gulf Coast 2 project, described in a later chapter.

CHAPTER 2

Research Approach and Conceptual Framework of the Highway System

2.1 Introduction

This chapter describes the approach followed in conducting the research. Given the multidisciplinary nature of the topic, the research utilized expertise in transportation engineering/operations, systems analysis, planning, climate science, policy, and construction/maintenance in a multidisciplinary research design. In particular, interaction with climate scientists was a critical factor in developing conclusions and recommendations. The chapter also presents a conceptual framework of how the highway system is viewed and how this framework can then be used to identify potential climate change–related impacts.

2.2 Research Approach

The research was conducted in six phases. Phase 1 identified climate change–related stresses that could affect the U.S. highway system over the next 40 years. This phase included identifying region-specific stresses and impacts for a range of climate-related changes. So, for example, coastal regions will be affected by sea-level rise and storm surges while non-coastal states might be affected more by higher temperatures. The impacts could relate to how roads are designed, how road networks are operated, and how ecological mitigation strategies are defined and managed. The United States was divided into 10 climate regions that could be defined with different climate and extreme weather characteristics. Climate models were used in defining these regions.

Phase 2 identified the current state of practice and knowledge in transportation adaptation planning through a literature search and interviews with adaptation leaders around the world. This resulted in a synthesis of typical practices and strategies that were being considered in many different locations.

Phase 3 developed a diagnostic framework that not only outlined the research steps that would be followed in this project, but also could be used in conducting adaptation planning for an agency. This phase also developed an evaluation approach for determining costs of adaptation strategies and understanding the expected benefits of implementing such strategies. The framework was applied to two of the regions identified in Phase 2.

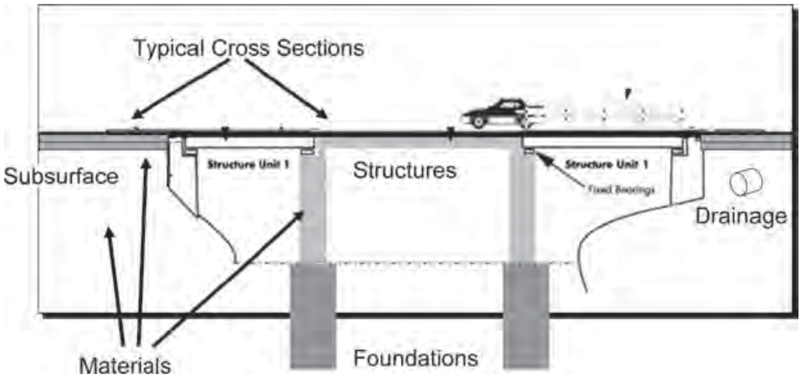
Phase 4 produced a guidebook on adaptation planning for practitioners (Part I of this volume) that was designed as a step-by-step approach to adaptation planning. In addition, a prototype web-based decision support tool was developed that allows users to identify those situations in which more design flexibility might be necessary to account for future climate-related risks [available on the Transportation Research Board (TRB) website: http://www.trb.org/Main/Blurbs/169781.aspx]. A spreadsheet tool was also developed that could be used to conduct a benefit–cost analysis on different adaptation actions at a particular location(available on the TRB website: http://www.trb.org/Main/Blurbs/169781.aspx). This phase also identified different institutional and organizational strategies for multijurisdictional collaboration and multiagency coordination.

The final phase, Phase 5, recommended future research.

2.3 Conceptual Framework of the Highway System

Prior to examining the probable impacts of climate change factors on highways (and opportunities for potential adaptation strategies), it is important to define what is meant by the highway system. A conceptual framework of the highway system helped guide the research tasks in terms of the types of impacts that might be expected from a changing climate as well as those elements of the highway system that might be at higher risk than others.

The idea of a highway-related conceptual framework for climate adaptation is not new. This approach was used in the writing of the resource paper for TRB *Special Report 290* in which the conceptual framework shown in Figure II.1



Source: Meyer (2008).

Figure II.1. Assets of a typical road segment.

was used to target potential components of road infrastructure design that could be affected by changes in environmental conditions (Meyer 2008). This conceptualization was the basis for a matrix that then indicated expected changes in environmental conditions and the influence on the design of the road network.

The concept shown in Figure II.1 was useful for this research, but it clearly needed to be expanded to include more than just a road segment and more than an interest in design since most of the highway system that will serve the next few generations is already built (and showing its age), and network-level land use patterns are largely set. For example, the intermodal connections that the road network serves are an integral part of the transportation system; a more "network-oriented" concept of the highway system is essential for conceptualizing this. Also the road right-of-way needs to be looked beyond because state DOTs are often involved in a range of activities (such as emergency response and environmental mitigation) that could be affected by changes in environmental conditions.

Perhaps most importantly, the range of state DOT activities that will be affected by such changes needed to be defined in a systematic and comprehensive way. Road design is important, but so too are the transportation services essential for sustaining society as the full range of activities that constitute what a state DOT and other transportation agencies do to develop and manage a road network—including operations, maintenance, and construction—is considered.

Three different frameworks were used to represent three scales of roadway design and operations that could be affected by climate change–related environmental stresses. The first is shown in Figure II.1 and represents a typical road segment. From the perspective of change in local environmental conditions due to changes in climate or weather, this representation is perhaps the most useful. However, as noted previously, a much broader picture of the potential impacts of climate change on transportation services and agencies is needed. The second framework expands the road segment to a corridor perspective, one that includes "beyond the right-of-way" concerns, such as wetland mitigation issues and emergency response. The third framework presents a network perspective, which expands the perspective even further to include system continuity of an already overtaxed and aging system as reflected in operations and maintenance policies and, from a physical network perspective, the connections between the road network and other components of the transportation system, such as intermodal terminals and stations.

2.3.1 A "Typical" Road Segment

There are several components and design issues that are common to most transportation facilities, including roads and highways, rail lines, runways, and transit facilities. The five key components to the design of a typical road segment are subsurface/foundation conditions, materials specifications, structures, typical cross sections, and drainage/erosion. Each is discussed in the following paragraphs.

Subsurface Conditions

The stability of a built structure depends upon the soils on which it is built. Geotechnical engineers focus their attention on the properties of different soil types and their behavior given different design loadings (see, for example, Budhu 2000 and Coduto 1999). The expected behavior of soils directly influences the design of foundations and support structures for the infrastructure itself. Various stresses act upon soil, including geostatic, horizontal, and shear stresses, as well as stress associated with the weight of structures built on the soil. The design of foundations for transportation facilities reflects the soil conditions, water table, dead weight of the structure, and forces that add to the dynamic loads being placed on the structure (Reese et al. 2006).

One of the important factors for subsurface design is the degree of saturation and expected soil behavior under saturated conditions. Changes in pore water pressure can have significant effects on the shear strength of soils, and in fact it is a change in soil shear strength that has caused many failures in ground slopes (e.g., mud slides). A good example of how subsurface conditions can affect design is the behavior of different soils under seismic forces and the resulting effects on built structures. The shifting or liquefaction of soils during a seismic event creates significant risks of unstable soil conditions, and thus the destabilization of structures built on top of the soils. Seismic codes have been enacted in many regions of the world focused in particular on dealing with the changing characteristics of foundation conditions during such extreme events (National Research Council 2003).

Materials Specifications

Transportation structures are constructed of materials selected for their performance under design loads and environmental conditions. Much of the original research in transportation during the 1940s and 1950s focused on improving the ability of materials to withstand the loads associated with transportation use while still remaining resilient in response to changes in environmental conditions. Transportation research engineers continue to improve the physical properties of both asphalt and concrete pavements. Pavements, as a transportation facility component, affect facility performance at a considerably large spatial scale and their performance can change dramatically given changing conditions, such as heavier vehicles, higher traffic volumes, more dramatic freeze–thaw cycles, or subgrade soil dynamics (saturation, erosion, etc.).

Construction materials have a significant influence on the design and performance of bridges as well. Steel, concrete, or timber bridges must each handle the dead weight and dynamic loads they will be subject to, and thus the strength and resiliency of the bridge materials become of paramount concern to the bridge engineer. In addition to the changing conditions mentioned previously, the strength and protection of materials used in the design might have to be enhanced to account for expected wind loads, increased moisture or humidity (that could accelerate corrosion), and (for bridges located in coastal regions) more violent storm surges.

Cross Sections and Standard Dimensions

Given the complexity of designing a transportation facility, and of all the subcomponents that it consists of, engineers often identify typical sections that are applicable to much of a given design corridor. A typical longitudinal cross section for the road shown in Figure II.1, for example, would show the depth of subgrade, pavement materials and thickness, width of lanes and shoulders, slopes of the paved surface, expected design of the area outside the paved surface, and other appurtenances that might be found in a uniform section of the road. As noted above, the type of pavement and design of the subgrade would reflect the environmental conditions found along the alignment. The slope of paved surface would be determined not only by the physical forces from the vehicles using the facility (e.g., superelevation), but also by the need to remove water from the paved surface. In areas where substantial precipitation would be expected, the slope of pavement might be slightly higher to remove water to the side of the road as soon as possible. Cross sections would also be developed for areas where designs would be different from the typical section, such as locations for culverts, special drainage needs, bridges, and other structures that would be close to the side of the road.

The design of each of the key components of the cross section usually reflects design standards that have been adopted by the owner of the facility, such as a transportation agency. Thus, design manuals are often available with standards for lane and shoulder widths, transverse slopes, radii for road curvature, dimensions of barriers, merge and exit areas, culverts, drainage grates, signing, and pavement markings. Most of these standards are based on field or laboratory studies, many of which occurred decades earlier.

Design criteria are also associated with such things as the vertical clearance over waterways and other roads. For example, the U.S. Coast Guard establishes vertical clearance guidelines for bridges over waterways, with the vertical clearance dimensions depending on the type of navigation occurring on the river. One of the lessons learned from Hurricane Katrina was that the probabilistic vertical clearance designed into many of the Gulf Coast bridges over water channels was too low to withstand the actual storm surge that went over the bridge deck and floated the decks off of their supports. The bridges have been rebuilt with a higher clearance over the water surface along with improved fasteners to the bridge piers.

Drainage and Erosion

Water is one of the most challenging factors to design for in transportation engineering. As noted previously, saturated or near-saturated soils can be a critical consideration in the design of a facility's substructure and foundations. In addition, runoff from impermeable surfaces such as bridge decks or road surfaces must be handled in a way that redirects water flows away from the facility itself, but which does not harm the surrounding environment. Standard designs for drainage systems, open channels, pipes, and culverts reflect the expected runoff or water flow that will occur given assumed magnitudes of storms. Something as simple as the design of a culvert entrance would be affected by the assumed surge of water that would flow through it with due consideration for consequences of exceedances and construction costs vs. failure risks.

Structures

In the context of this report, structures will primarily refer to bridges. Consistent with the previous discussion on how engineers account for different physical forces when developing a design, civil engineering has a long history of research and practical experience with understanding how such forces act upon buildings and bridges [see Ellingwood and Dusenberry (2005) for an overview of how building codes have evolved over time in response to new types and degrees of structural loading]. The engineering design process is based on understanding the likely loads or forces that will be applied to the structure (note the practice of assigning a factor that represents how important the bridge is) and developing a design that provides a level of resistance to these forces that will exceed expected loads. The current approach toward bridge design is to consider the inherent uncertainty in expected loads and resistance factors that a bridge will be exposed to, and thus probabilistic methods are used to incorporate such uncertainty. The primary focus of such an approach is to increase the reliability of the structure over its lifespan while considering the economic costs of failure versus construction/rehabilitation cost. AASHTO's most recent bridge design manual incorporates risk into the calculations of bridge design parameters, although the economic costs of failure are not totally considered.

Bridges over water present a special challenge to bridge engineers. According to the *AASHTO LRFD Bridge Design Specifications* (AASHTO 2004a), waterway crossings should be studied with respect to the following factors:

- Increases in flood water surface elevations caused by the bridge
- Changes in flood flow patterns and velocities in the channel and on the floodplain
- Location of hydraulic controls affecting flow under the structure or long-term stream stability
- Clearances between the flood water elevations and low sections of the superstructure to allow passage of ice and debris
- Need for protection of bridge foundations and stream channel bed and banks
- Evaluations of capital costs and flood hazards associated with the candidate bridge alternatives through risk assessment or risk analysis procedures

As can be seen in this list, the assumed behavior of the water body below the bridge significantly affects how the design of the bridge proceeds. The design of bridges in coastal areas has received renewed attention given the experience with Hurricane Katrina. According to a position paper of the Federal Highway Administration (FHWA 2005), "in the coastal environment, design practice assumes that flood events would essentially behave in a manner similar to a riverine environment. However, bridge failure mechanisms associated with recent storm events have resulted in a re-evaluation of these assumptions. The result is a need to differentiate how FHWA considers the state of practice to hydraulically design bridges in the coastal environment." As noted in the paper, the hurricane damage to the Gulf Coast bridges resulted primarily from the combination of storm surge and wave crests. However, most state DOTs assume a riverine environment when designing bridges, which assumes a 50-year storm event (this approach is codified in state drainage manuals, AASHTO drainage guidance, and in FHWA floodplain regulations). The result of this assumed frequency of storm is that designs do not consider the effect of wave actions on the bridge. In other words, according to their own regulations and design guidelines, state DOTs can consider a storm surge, but not additional wave actions.

As noted by the FHWA, "state DOTs find themselves in the position that their own regulations and guidelines do not permit them to consider alternative bridge design frequency criteria" (FHWA 2005). The FHWA recommended that a 100-year design frequency be used for interstates, major structures, and critical bridges that would consider a combination of wave and surge effects, as well as the likelihood of pressure scour during an overtopping event (water levels going over the structure). The consideration of a super flood frequency surge and wave action (that is, the 500-year design frequency) was also suggested. It was also recommended that risk and cost assessments be conducted. Note that the marginal costs of additional safety factors must also be kept in mind.

Long-span bridges, especially over water, present a special challenge in two respects. First, very long bridges have to account for wind forces, which can be quite substantial in areas where the topography results in a "canyon effect," that is, high hills or cliffs that concentrate and thus make more powerful the winds striking the bridge. For suspension or cable-stayed bridges, these wind forces must be accounted for in the design strength of the support structure and in the level of deflection or flexibility designed into the bridge itself (Simiu and Scanlan 1996). For long-span bridges, engineers conduct wind tunnel tests of different sections of a proposed design to assess section behavior under varying wind conditions.

Second, columns or piers that are located in water are subject to scour, that is, the erosion of the river or stream bed near the column foundation. The majority of bridge failures in the United States are the result of scour (AASHTO 2004a) in that the flow of water currents at the column base can erode the stability of the column foundation. The FHWA requires that bridge owners evaluate bridges for potential scour associated with the 100-year event (known as the base flood) and to check scour effects for the 500-year event (known as the super flood). If floods or storm surges were expected to occur more frequently or channel flows were to become more turbulent, the engineer would potentially have to rethink the design of such foundations (Sturm 2001).

The foregoing description of the different components of a typical roadway segment does not cover all of the different considerations that would enter into the design thought process of the engineer. However, it does illustrate the important influence of standards and guidelines in the design process in response to expected environmental factors. In addition, the discussion suggests some of the design categories in response to changes in these environmental conditions, and in particular those related to climate change, and their implications as to how engineers should design a transportation facility.

2.3.2 A Corridor Perspective

The potential impacts of changing environmental conditions due to climate change on a typical road segment would of course accumulate over a corridor and throughout the network where similar circumstances exist. At the corridor level, disruptions to passenger and freight movements could be significant if such disruptions occur over a long period (e.g., bridge collapse) and/or if very few alternative routes exist. The impacts of many of the weather-related disruptions that have occurred in recent years—Midwestern floods and corresponding impacts on Interstate highways and mail rail lines, Washington State floods and closure of Interstate 5, drought and corresponding wildfires and closure of Interstates in Colorado, and flooding and highway/rail closures in Vermont—have been primarily felt at the corridor level. By affecting corridor mobility and accessibility, weather-related disruptions have effects on through traffic (and thus economic impacts beyond the corridor) as well as on corridor-level traffic that have origins and destinations within the corridor (and thus economic impacts in adjacent communities).

With respect to environmental conditions, if subsurface conditions are affected because of changes in soil moisture in one location, there is a strong possibility that this effect will be found in many other parts of a network, or certainly within a corridor (where similar soil conditions could be expected). Figure II.2 illustrates other types of concerns that might be found within a road corridor over and above those

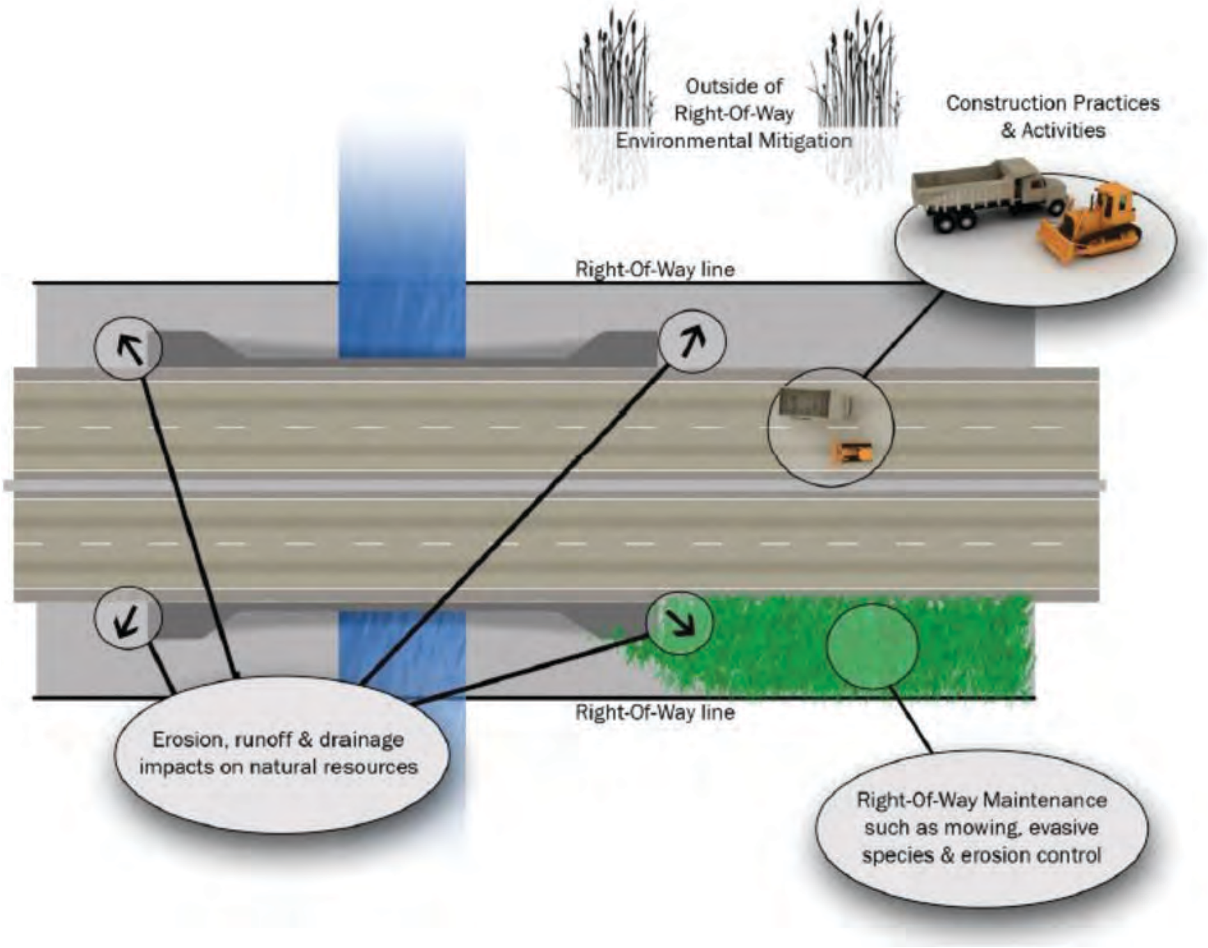


Figure II.2. Corridor-level impacts of changing local environmental conditions.

related to specific design components. Most of these concerns relate to either maintenance practices or environmental mitigation and/or avoidance strategies.

Outside-of-Right-of-Way Environmental Mitigation

Many transportation agencies have developed environmental mitigation programs that focus on replacement assets outside of a corridor's right-of-way. An example of this includes the concept of wetland banking for wetlands that are disturbed as part of a construction process. With changing environmental conditions due to long-term climate change, the ability to develop ecologically sound and functionally replicating ecological mitigation strategies could be seriously hindered. For example, some state DOTs are currently taking into account projected sea-level rise when identifying wetland mitigation sites as many of the previous wetland mitigation sites have been located in estuaries that are likely to be impacted by sea-level rise.

Erosion, Drainage, and Runoff Impacts

Changes in precipitation, both overall levels and rainfall intensities, are considered two of the major changes likely to be experienced in the future. The design implications of these changes to such things as culverts and road-related drainage systems were discussed in the previous section. The impact noted here is the likelihood of increased runoff and erosion impacts on surrounding land uses and ecological resources. Increased runoff, with higher volumes and perhaps higher intensities, could have significant impacts on nearby water bodies, such as streams and rivers. Such a possibility might require new means of handling erosion and runoff, primarily by reducing volumes or diverting flows away from sensitive areas.

Right-of-Way Maintenance

Studies overseas have identified changing right-of-way maintenance operations as one of the potentially important impacts of changes in climate on transportation agency practices. These impacts could relate to changes in growing season (and thus more or less mowing), invasive species infestation, snow removal, and flooding caused by backed up drainage systems. Synergistic effects of climate change such as unseasonable freezing rain on trees already weakened by increased predation from invasive species could contribute to widespread power outages and road closures in the wake of storm events. It will be difficult to predict a specific point in time when such issues might become a serious concern to a transportation agency. More likely, changes in maintenance practices will be phased in as "emergencies" become more "routine," and it becomes apparent that current approaches are no longer meeting the needs of the highway system.

Construction Practices and Activities

Changes in temperature and precipitation and the corresponding need to utilize different construction materials could affect construction practice. In addition, a lengthening or shortening of the construction season could also influence a transportation agency's construction program. Transportation agency adaptation plans from overseas identify an increasing frequency of more intense storms as affecting construction costs and scheduling, as well as the need to provide improved training to construction workers who might have to work more often in inclement weather.

2.3.3 A Network Perspective

The final perspective on potential climate change impacts on the highway system relates to the overall management of the highway network, including building and protecting the agency's assets as well as developing system management strategies for expected disruptions (see Figure II.3).

Alternate Routes and Corresponding System Operations Strategies

One of the likely characteristics of future weather conditions is more intense storms (or extreme events as they are called in the literature) and a corresponding disruption to the highway network. The impacts of Hurricanes Katrina and Sandy on all aspects of a region's transportation network, including highways, transit facilities/services, airports, ports, and freight terminals, have been well documented. Responses to events such as these will require strategic and coordinated response plans to not only deal with the immediate aftermath, but also help speed the recovery process. In metropolitan areas, in particular, where traffic management centers have been established to coordinate and guide traffic flows, it is likely that such centers will be used more frequently to respond to weather-related events and that improved emergency response systems including 511 Traveler Information systems be developed and deployed as part of an overall adaptive management strategy. Vermont's experience after Tropical Storm Irene of establishing such coordination centers and using Google maps and information sources was one of the lessons learned (VTrans 2012b).

Intermodal Connections

Although this project is focused on the "highway system," in reality today's transportation system consists of

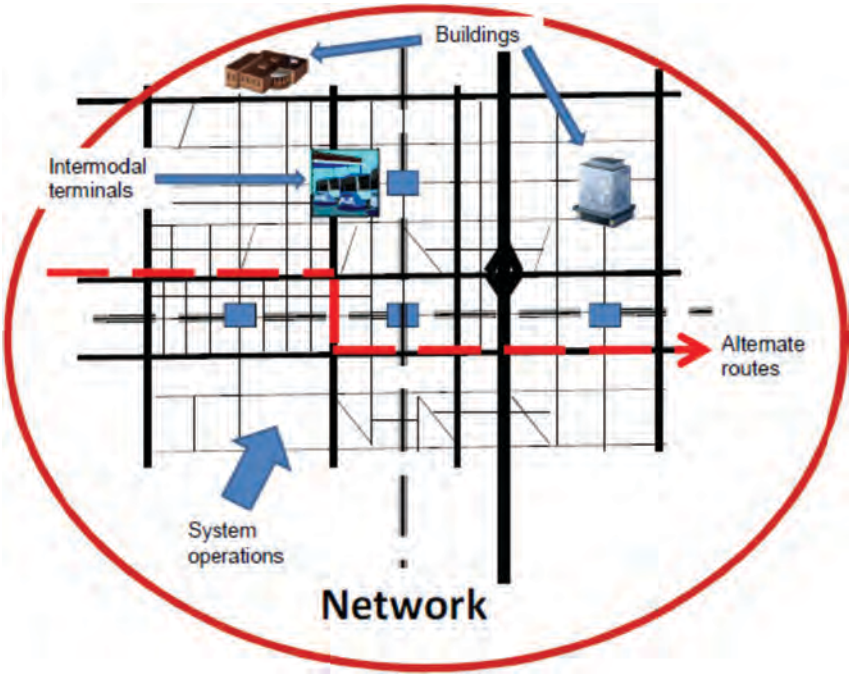


Figure II.3. Network-level impacts of changing local environmental conditions.

interconnections among different modes serving a variety of purposes. Examples of such interconnections include intermodal passenger and freight terminals, park and ride lots, access roads to freight intermodal facilities, and pedestrian/bicycle facilities connecting to transportation stations or terminals. Even though a transportation agency might not have jurisdiction over intermodal facilities, it makes sense for someone to view the facility and the access to the facility as one part of a larger system. Strategies to protect road access should be combined with strategies to protect the facility itself and maintain vital transportation services in a "just in time delivery" economy.

Location Engineering (where to put the facility to begin with)

Designs for new or relocated transportation facilities always include location studies to determine where to build the facility. Such efforts are often associated with much broader environmental impact analyses that examine a range of alternative alignments and design characteristics. Location studies themselves often do not have specific design criteria associated with where facilities will be located, although factors such as right-of-way width, roadway curve radii, and vertical slope limitations for different types of facilities will constrain designs to certain design footprints. In addition, as part of environmental analyses, a fatal flaw analysis often identifies areas or sites so environmentally sensitive that the designer will stay clear of these locations. The important question with respect to transportation facility location studies is how areas that might be susceptible to climate change effects, such as coastal or low-lying areas, might be evaluated for suitability.

Building and Protecting Agency Assets

Transportation agencies are often owners of a substantial number of buildings, shelters, and other physical assets used by employees in the day-to-day operations of the agency. Although such assets are not often considered in most adaptation studies, which tend to focus on the transportation network itself, agency managers will have to deal with managing such assets with changing local environmental conditions. This could mean developing strategies ranging from enhanced protection from wider temperature ranges to protection from inundation. It is likely that as climate and weather conditions change, the building industry will change with it, including the use of innovative materials to better handle new loads and stresses on the structures. So, in such cases, these changes will be incorporated into building and materials specifications. However, especially in the case of state transportation agencies, which have buildings spread out over an entire state, the need to be cognizant of changing local environmental conditions and their potential impact on the agency's assets could be an important concern to future managers.

2.4 Summary

This chapter presented a multilevel perspective on potential impacts of climate change on the built and yet-to-be-built highway system. Each level examines a particular scale of application and in many ways can be viewed as adding a more complex and strategic management role. For example, many of the design changes that might be necessary at the typical road-segment level can be incorporated into design standards and agency standard operating procedures. However, dealing with system-wide operations strategies or a more comprehensive management of an agency's physical assets would imply a higher level of management involvement to deal with an already built, increasingly congested, and aging system.

CHAPTER 3

Current Practice in Adaptation Planning and Adaptive Management

3.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* discussed how combining knowledge about climate science, disaster management, and adaptation can inform discussions about managing the risks of extreme events and disasters in a changing climate (IPCC 2012). It included a wide range of options used by organizations to reduce exposure and vulnerability, and improve resilience to climate extremes. The report also made a number of observations about likely extreme climate-related events in the 21st century, including increases in the frequency of heavy precipitation; increased frequency of warm daily temperature extremes; decreases in cold extremes; increases in heat wave length, frequency, and intensity; increases in wind speeds of tropical cyclones; droughts intensifying in central North America; upward trends in extreme sea levels; and the projected precipitation and temperature changes that imply changes in floods.

The report further suggested that approaches to climate change adaptation and disaster risk management can be complementary and effectively combined, as well as complement other community goals. For example, such efforts can help "address development goals, improve livelihoods and human well-being" (IPCC 2012). These so-called "no or low regrets" measures include early warning systems, land use planning, sustainable land management, and ecosystem management. These measures help reduce vulnerability to projected changes in climate and also tackle underlying drivers of change in extreme weather or climate. These measures are typically recommended when uncertainties over future climate change directions and impacts are high. For example, continued maintenance of existing transportation infrastructure to minimize the chances of flooding or other damage that might occur will help prepare agencies before more permanent adaptation plans can be implemented.

As suggested by this report, adaptation planning and adaptive management is a relatively new concept, especially in the United States. Table II.1 presents the results of a recent review of climate change adaptation frameworks that have been generally applied to all sectors and those that have focused on transportation (Wall and Meyer 2013). This review summarized the current limitations and barriers to further development that characterized many of these efforts as being: "(1) data limitations—limited or inaccessible infrastructure data; limited usable climate data; (2) an inadequate treatment of risk—reconciling the immediate need for action with the perception of distant consequences; the qualitative treatment of risk; defining acceptable levels of risk; and (3) the lack of sufficient financial resources. Transportation agencies and organizations—particularly independent and private sector organizations—identified additional limitations or barriers: (4) interdependencies and regulatory barriers and (5) uncertainty in future system demand that causes uncertainty in the need for adaptation." The following sections review adaptation practices and methodologies that have been tried in practice in both the United States and internationally.

3.2 U.S. Perspectives

3.2.1 Federal Government

Much of the focus of federal efforts at transportation and adaptation has been on the activities of federal agencies themselves. The Council on Environmental Quality (CEQ) has issued "Instructions for Implementing Climate Change Adaptation Planning in Accordance with Executive Order 13514." The Executive Order requires each federal agency to evaluate agency climate change risks and vulnerabilities to manage both the short- and long-term effects of climate change on the agency's mission and operations. A climate change adaptation policy was adopted by the U.S. DOT in 2012 that mandated the integration of climate change impacts and adaptation into

Table II.1. General and transportation infrastructure-specific adaptation frameworks.

Framework - General Infrastructure	Country	Agency/Organization
Climate Change Risks to Australia's Coast: A First Pass National Assessment	Australia	Department of Climate Change (2009)
Climate Change Risks for Coastal Buildings and Infrastructure: A Supplement to the First Pass National Assessment	Australia	Department of Climate Change and Energy Efficiency (2011)
Infrastructure and Climate Change Risk Assessment for Victoria	Australia	Victorian Government (CSIRO et al. 2007)
Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure	Canada	Public Infrastructure Engineering Vulnerability Committee (PIEVC), Engineers Canada (2008)
PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment	Canada	PIEVC, Engineers Canada (2009)
Adapting to Climate Change: A Risk-Based Guide for Ontario Municipalities	Canada	Ontario Ministry of Municipal Affairs and Housing (Bruce et al. 2006)
Adapting to Climate Change: A Risk-Based Guide for Local Governments	Canada	Natural Resources Canada (Black et al. 2010)
Ahead of the Storm: Preparing Toronto for Climate Change	Canada	Toronto Environment Office (2008)
Climate Change Risk Management Strategy for Halifax Regional Municipality	Canada	Halifax Regional Municipality (Dillon Consulting and de Romilly & de Romilly 2007)
The National Flood Risk Assessment	Scotland	Scottish Environmental Protection Agency (SEPA) (2011a)
Flood Risk Management Strategies and Local Flood Risk Management Plans	Scotland	Scottish Environmental Protection Agency (2011b)
Climate Change Adaptation in New York City: Building a Risk Management Response	United States	New York City Panel on Climate Change (2010)
Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments	United States	King County (WA) Executive (Center for Science in the Earth System and King County 2007)
Impact of Climate Change on Road Infrastructure	Australia	Austroads (Norwell 2004)
Risk Management for Roads in a Changing Climate (RIMAROCC)	European Union	ERA-NET (Bies et al. 2010)
Climate Change Uncertainty and the State Highway Network: A Moving Target	New Zealand	Transit New Zealand (Kinsella and McGuire 2005) [now NZ Transport Agency]
Climate Change Effects on the Land Transport Network Volume One: Literature Review and Gap Analysis	New Zealand	NZ Transport Agency (Gardiner et al. 2008)
Climate Change Effects on the Land Transport Network Volume Two: Approach to Risk Management	New Zealand	NZ Transport Agency (Gardiner et al. 2009)
Scottish Road Network Climate Change Study	Scotland	Scottish Executive (Galbraith et al. 2005)
Scottish Road Network Climate Change Study: Progress on Recommendations	Scotland	Transport Scotland (Galbraith et al. 2008)
Scottish Road Network Landslides Study	Scotland	Scottish Executive (Winter et al. 2005)
Adaptation Reporting Powers received reports*	United Kingdom	Department of Environment, Food and Rural Affairs (2012)

(continued on next page)

Table II.1. (Continued).

Framework - General Infrastructure	Country	Agency/Organization
Climate Change Adaptation Strategy	United Kingdom	Highways Agency and Parsons-Brinckerhoff (2008)
Climate Change Adaptation Strategy and Framework	United Kingdom	Highways Agency (2009)
Highways Agency Climate Change Risk Assessment	United Kingdom	Highways Agency (2011)
*Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model***	United States	Federal Highway Administration (2012c)
Climate Change & Extreme Weather Vulnerability Assessment Framework	United States	Federal Highway Administration (2012b)

* Twenty-three agency reports were reviewed under the Department of Environment, Food and Rural Affairs reporting powers requirement. A full agency list can be found at http://www.defra.gov.uk/environment/climate/sectors/reporting-authorities/reporting-authorities-reports/

** This includes five pilot-program case study reports: Metropolitan Transportation Commission et al. (2011), North Jersey Transportation Planning Authority (2011), Oahu Metropolitan Planning Organization (SSFM International 2011), Virginia DOT (2011), Washington DOT (Maurer et al. 2011)

Source: Wall and Meyer (2013)

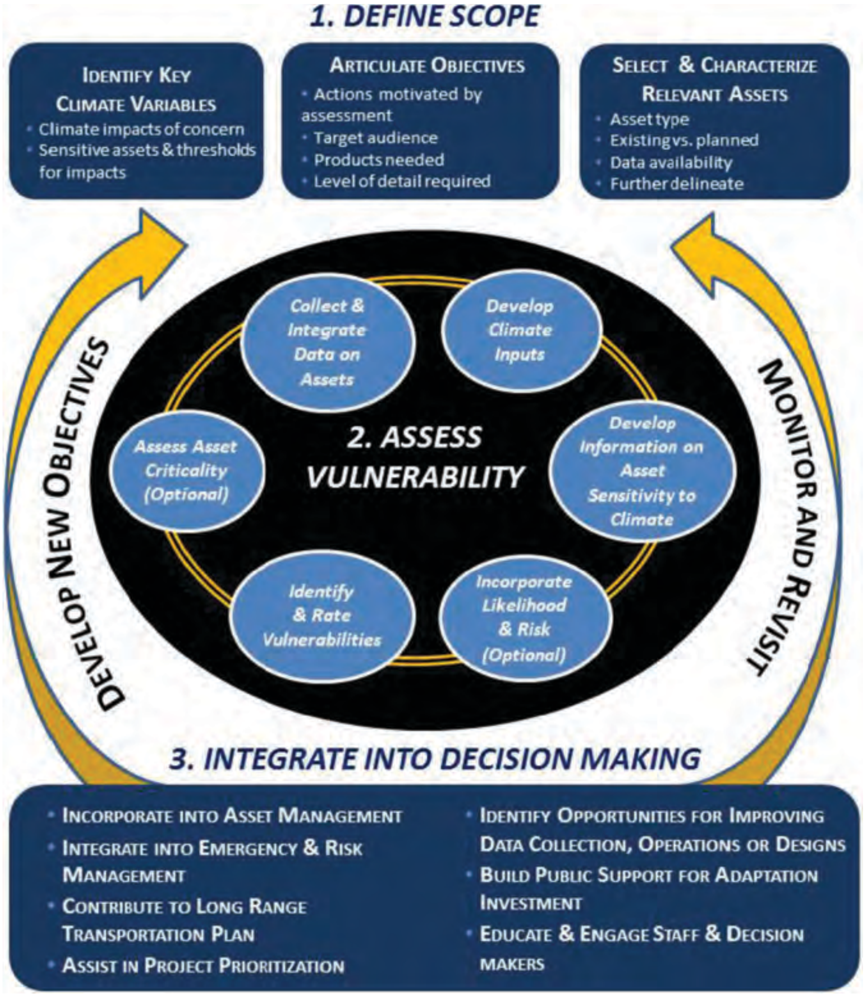
the planning, operations, policies, and programs of the agency (U.S. DOT 2011). The policy statement also directed the U.S. DOT modal administrations to encourage state, regional, and local transportation agencies to consider climate change impacts in their decision making.

The CEQ also proposed draft guidance in 2010 on how climate adaptation could be considered as part of the National Environmental Policy Act (NEPA) process (CEQ 2010). The draft guidance recommended that climate change stressors should be considered for projects that have long useful lives or that are located in areas that are considered vulnerable to specific effects of climate change (such as increasing sea level or ecological change). The draft guidance proposed to use the scoping process to establish the degree to which "aspects of climate change may lead to changes in the impacts, sustainability, vulnerability, and design of the proposed action and alternative courses of action." The NEPA requirement to describe the "affected environment" of a proposed action that might have significant impact was pointed to as the most logical step in the process where observed and projected effects of climate change should be considered. Once the relevant climate stressors are identified, the agency can then determine the extent to which any proposed action will be affected by such change or the degree to which the action might exacerbate the likely impact. This includes not only the potential impact on the surrounding environment, but also the effects on vulnerable populations and nearby communities.

The draft guidance suggests that climate change can affect the environment of a proposed action in a variety of ways—affecting the integrity of a project by exposing it to a greater risk of extreme conditions (e.g., floods, storm surges, or higher temperatures); increasing the vulnerability of a resource, ecosystem, or human community; and possibly magnifying the damaging strength of certain effects. As of the date of this report, this guidance has not been finalized.

Within the U.S. DOT, the activities of the FHWA and the FTA have been notable in fostering a leadership position on transportation adaptation. The FHWA began its involvement by hosting a peer workshop on adaptation in December of 2008 that involved metropolitan planning organization (MPO) and state DOT officials interested in climate adaptation. The workshop concluded by calling for a national adaptation strategy and for the FHWA and other federal agencies to provide relevant and actionable guidance, research, and policy documents on the topic (ICF International 2012). The FHWA followed through by releasing a literature review, high-level climate data by U.S. regions, and a conceptual model to assess the vulnerability of transportation infrastructure to climate change. This model was pilot tested in five locations from 2011 to 2012 (see the text box for reports on these pilot studies), and the conceptual model was modified to reflect the lessons learned from the pilot studies (FHWA 2012a; see Figure II.4).

In addition, FHWA initiated a major study on the impacts of climate change on transportation systems and infrastructure in the U.S. Gulf Coast. Phase I of this study examined the likely climate change in temperature, precipitation, sea-level rise, and storm surge along with impacts on highway, water, air, rail, and transit modes in the Gulf Coast states (i.e., Texas, Louisiana, Mississippi, and Alabama) and identified adaptation measures. The study discussed four major conceptual factors to consider with respect to transportation-related



Source: FHWA (2012a)

Figure II.4. FHWA's Climate Change & Extreme Weather Vulnerability Assessment Framework.

climate concerns—exposure to climate stressors, asset vulnerability to these stressors, asset resilience, and adaptive capacity. It also examined how transportation agencies can incorporate climate change considerations into transportation decision making. Phase II, starting in 2011, is focusing on Mobile, Alabama, by conducting an adaptation assessment and engineering analysis of potential adaptation strategies. A goal of this phase is to make this adaptation process replicable, so that other regions can conduct similar assessments (FHWA 2012a).

The FTA has sponsored seven pilot projects that will examine different adaptation strategies that were to fit within the transit agency's structure and operations. Two of the pilot projects will demonstrate the integration of climate impacts with an asset management system. These pilot studies will provide practical experience with how a transit agency can consider climate change-related adaptation strategies in day-to-day operations (FTA 2013).

Perhaps the most impactful federal adaptation policy has been issued by the U.S. Army Corps of Engineers (USACE). In this policy, the planning, engineering, designing, operating, and maintenance of Corps infrastructure must be sensitive to sea-level change and "must consider how sensitive and adaptable (1) natural and managed ecosystems and (2) human and engineered systems are to climate change and other related global changes" (USACE 2011). Corps engineers are to define alternatives that are formulated and evaluated for a range of possible future rates of sea-level change, represented by "low," "intermediate," and "high" sea-level change scenarios, both "with" and "without" project conditions. In addition, they are to determine "how sensitive alternative plans and designs are to these rates of future local mean [sea-level change], how this sensitivity affects calculated risk, and what design or operations and maintenance measures should be implemented to minimize adverse consequences while maximizing beneficial effects."

References for the FHWA Pilot Studies on Climate Change Vulnerability

Metropolitan Transportation Commission, Caltrans, and Bay Conservation and Development Commission, *Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project: Briefing Book*, November 2011. http://www.mtc.ca.gov/planning/climate/Rising_Tides_Briefing_Book.pdf

New Jersey Transportation Planning Authority, *Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure*, April 2012. http://www.njtpa.org/Plan/Element/Climate/documents/CCVR_REPORT_FINAL_4_2_12_ENTIRE.pdf

Oahu Metropolitan Planning Organization, *Transportation Asset Climate Change Risk Assessment*, November 2011. http://www.oahumpo.org/climate_change/CC_Report_FINAL_Nov_2011.pdf

University of Virginia and Virginia Department of Transportation, *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure, Hampton Roads, VA Pilot*, November 2011. http://www.virginia.edu/crmes/fhwa_climate/iles/finalReport.pdf

Washington State Department of Transportation, Climate Impacts Vulnerability Assessment, November 2011. http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf

The policy suggests multiple approaches for comparing and selecting desirable alternatives, including:

1. Use a single scenario and identify the preferred alternative under that scenario. Then evaluate this alternative's performance with other scenarios to determine overall performance.
2. Compare all alternatives against all scenarios. This approach does not necessarily result in the "best" alternative for a particular scenario, but rather allows one to be selected that is "more robust in the sense of performing satisfactorily under all scenarios."
3. Modify the results of approaches 1 or 2 to incorporate alternative features that improve overall life-cycle performance.
4. Explicitly consider uncertainty, and how sea-level change scenarios affect risk levels.

3.2.2 State Governments

Many state governments developed Climate Action Plans in the mid- to late 2000s as a means of primarily assessing greenhouse gas reduction strategies. Very few discussed adaptation as a challenge facing government agencies. For those transportation agencies that have considered adaptation concerns, most efforts are in the early stage of identifying the major climate drivers, risks and vulnerabilities, and high-level adaptation strategies. Only a handful of agencies have implemented adaptation actions. Where such efforts have occurred, they are described in the following sections. It is interesting to note that almost all of the U.S. leaders in adaptation are in coastal locations, presumably in response to the risks presented by sea-level rise and storm surge.

Alaska

The Alaska Department of Transportation and Public Facilities is in an unusual position in that its program includes non-transportation public facilities, giving it a wider jurisdiction than most DOTs. Among its concerns are communities that are in jeopardy of accelerated coastal erosion from winter storms due to lack of protective sea ice. Several of these communities developed relocation plans. As a result, much of the DOT's adaptation activities focus on shoreline protection and relocation. One airport whose runway was directly threatened by coastal erosion has already been relocated. An USACE project has armored the shoreline of one of the communities as well. In addition, the Alaska Department of Transportation and Public Facilities has dedicated funding to combat permafrost thawing under highways and is also actively working on drainage improvements and evacuation routes and shelters.

California

In response to a gubernatorial executive order, the California Department of Transportation (Caltrans) developed guidelines for considering sea-level rise in project planning documents (Caltrans 2011). As noted in the guidance, not only will enhancing the design features of structures likely be a consideration, but so too will be increasing costs for permit fees and mitigation. A three-part screening process was recommended, in essence answering the following questions:

1. Is the project located on the coast or in an area vulnerable to sea-level rise?
2. Will the project be impacted by the stated sea-level rise?
3. Is the design life of the project beyond year 2030?

If it is determined that sea-level rise needs to be considered as part of the design, the project initiation document must provide a detailed discussion of potential impacts and how they might affect the design.

California, Oregon, and Washington

Although not a state study, the National Research Council was requested by California, Oregon, and Washington to investigate sea-level information at state, national, and global scales to determine coastal vulnerability and response to sea-level rise; to improve models and forecasts; to develop research priorities; and to develop decision support tools for a variety of users, including the USACE, which needs sea-level information to guide water resource investment decisions (National Research Council 2012).

Global mean sea level is rising primarily because global temperatures are rising, causing ocean water to expand and land ice to melt. However, sea-level rise is not uniform. Sea-level rise along the coasts of California, Oregon, and Washington depends on the global mean sea-level rise and also on regional factors, such as ocean and atmospheric circulation patterns in the northern Pacific Ocean, the gravitational and deformational effects of land ice mass changes, and tectonics along the coast.

The projections show that for California south of Cape Mendocino the sea level is expected to rise because of land subsidence in California, but to the north sea level will decrease because of land uplift in Oregon and Washington. For the California coast south of Cape Mendocino, the study projects that sea level will rise 1.6 to 12 inches (4–30 centimeters) by 2030 relative to 2000, 4.7 to 24 inches (12–61 centimeters) by 2050, and 16.5 to 66 inches (42–167 centimeters) by 2100. For the Washington, Oregon, and California coasts north of Cape Mendocino, sea level is projected to change between –1.6 inches (–4 centimeters) (sea-level fall) and +9 inches (+23 centimeters) by 2030. The combination of land uplift and gravitational and deformational effects reduces the threat of future sea-level rise for Washington and Oregon. However, the land is rising along the Washington and Oregon coasts likely because inter-seismic strain is building in the Cascadia Subduction Zone. A great earthquake (magnitude larger than 8 on the Richter Scale), which has occurred in the area every few hundred to 1,000 years, would cause some coastal areas to immediately subside and relative sea level to suddenly rise. If this occurs, relative sea level could rise an additional meter or more over projected levels.

Most of the damage along the California, Oregon, and Washington coasts is caused by storms—particularly the confluence of large waves, storm surges, and high astronomical tides during a strong El Niño. The water levels reached during these large, short-term events have exceeded mean sea levels projected for 2100, so understanding their additive effects is crucial for coastal planning in this area.

Maryland

In January 2011, the Maryland Commission on Climate Change produced the *Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change, Phase II: Building Societal, Economic, and Ecological Resilience* (Boicourt and Johnson 2010). Whereas Phase I established the background on sea-level rise, this report developed sector-based adaptation strategies. Transportation is included with "Population Growth and Infrastructure." One of the key policy recommendations requires state agencies to integrate climate change adaptation strategies into policies and programs. The report also called for the Maryland DOT to:

- Conduct a comprehensive analysis of the vulnerability of Maryland's infrastructure,
- Assess the economic costs resulting from severe weather events,
- Develop operation contingency plans for critical infrastructure,
- Identify investment needs to prepare for future weather emergencies, and
- Address funding and revenue constraints for current and future infrastructure needs.

Maryland is one of the first states to begin systematically inventorying the vulnerability of its transportation assets to climate change, beginning with vulnerability to sea-level rise. Sea-level rise is an initial priority for Maryland's adaptation plan because of that state's particular vulnerability—it has more than 4,000 miles of coastline, much of it low-lying land on the Chesapeake Bay at risk to inundation (in fact, in the past century several islands in the Bay have disappeared under the rising water levels). The state has developed a high-resolution LIDAR data set to allow development of sea-level rise inundation models along its coastlines. Maps have been created for 14 coastal counties, depicting lands at potential risk.

In 2013, Maryland's governor signed an executive order, *Climate Change and Coast Smart Construction*, to increase the state's long-term resiliency to storm-related flooding and sea-level rise. The executive order directed all new and reconstructed state structures, as well as other infrastructure improvements, be planned and constructed to avoid or minimize future flood damage. In particular, the state's Department of General Services was directed to update its architecture and engineering guidelines to require new and rebuilt state structures to be elevated 2 or more feet above the 100-year base flood level.

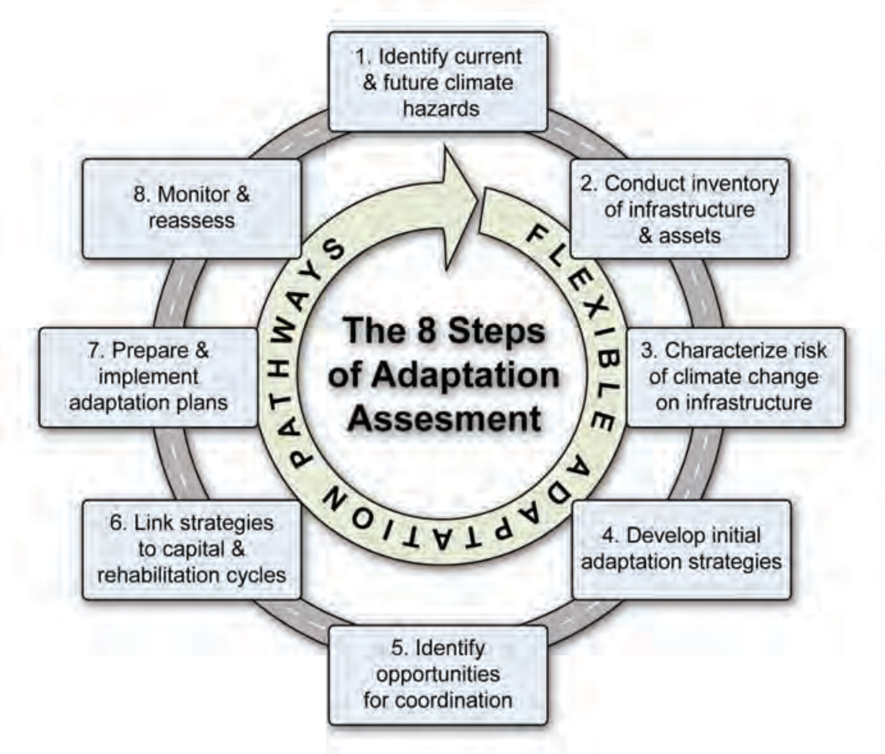
New York

New York State has conducted a state-level assessment of climate change impacts specifically designed to assist in the development of climate adaptation strategies (New York State Energy Research and Development Authority 2011). It forecasts climate change by regions of the state and acknowledges the need to plan for and adapt to climate change impacts in a range of sectors including transportation. Strategies include doing engineering-based risk assessments of assets and operations. Other strategies include the protection of coastal transportation infrastructure with levees, sea walls, etc.; relocation of critical systems to higher ground; lengthening airport runways; using heat-resistant construction materials; and changing engineering specifications related to climate. New York's updated adaptation assessment steps are shown in Figure II.5.

3.2.3 Regional/Local Governments

Asheville, North Carolina

The French Broad River MPO, the regional planning agency for Asheville, North Carolina, was one of the first MPOs in the United States to incorporate climate change considerations into its long-range transportation plan. The adaptation planning approach focused on climate variability that was likely to occur in the region and system vulnerability and resiliency (French Broad River MPO 2010). For example, the plan noted that in its study area, which is primarily mountainous and full of forests, extended drought increases the danger of wildfires and their associated smoke hazard, while the intense storms and increased rainfall increase the occurrence of flooding, landslides, and dam breaches. From an analysis of expected climate extremes and locations of key transportation facilities, the hottest locations in the study area are in the valleys where major transportation corridors were located, and the coldest locations were in the mountains. Therefore, the plan noted that "roads in the valleys will need to be designed to withstand greater periods of extreme heat, while the roads in the higher



Source: New York State Energy Research and Development Authority (2011)

Figure II.5. New York State adaptation assessment steps.

elevations will need to be designed to withstand colder temperatures and icing events." The types of climate change–related impacts anticipated in the region include the following:

1. Increase in flooding occurrence and intensity, especially tied to severe storms. This increased flood intensity will affect many bridges and large sections of key transportation arteries.
2. Increase in landslides due to severe storms and continued road building associated with steep slope development. Increased rain is a trigger for an increasing number of landslides.
3. Wildfire/smoke impacts due to more intense periods of drought.
4. Dam breach analysis should be performed and early warning systems created for all major dams in the area that are up dip from major transportation corridors.
5. Staging areas for fuel supplies should be strategically placed based on these hazards. There is a relatively modest amount of local fuel storage, and many of these locations are in floodplains.

The analysis process was straightforward; proposed long-range transportation plan projects were overlaid on maps of the region's 500-year floodplain, wildfire risk, and steep slopes (prone to landslides). Figure II.6, for example, shows study area highways that are located in the 500-year storm floodplains. By following this approach, projects that had beneficial impacts

Source: French Broad River MPO (2010).

Figure II.6. Identifying vulnerable highway facilities, Asheville, North Carolina.

for climate adaptation over and above the benefits associated with the project justification process were indicated on the prioritization list.

King County, Washington

King County developed its *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* in conjunction with its Climate Plan (Center for Science in the Earth System and King County 2007). The County formed an interdepartmental climate change adaptation team, partnering with the Climate Impacts Group at the University of Washington, for scientific expertise. Each year, the Executive Action Group is required to produce a report that provides updates on the county's climate planning.

Actions already underway by King County Road Services Division include evaluation of higher flows on bridge and culvert design as well as seawall modifications. The Road Services Division is rebuilding over 57 bridges and 40 culverts to improve stream flows and endure the most significant impacts of climate change.

Houston

The Houston–Galveston Area Council formed the Foresight Panel on Environmental Effects in 2007 to assess possible climate change impacts in the Houston region. In 2008, the panel produced the *Foresight Panel on Environmental Effects Report* that highlighted its findings. The report, piggybacking on data from the FHWA's Gulf Coast Study, outlined projected climate changes for the Houston metro area and their impacts on infrastructure, public facilities, ecosystems, and public health. A geographic information system (GIS)–based study of sea-level rise and flooding scenarios helped to illustrate vulnerable infrastructure and facilities.

New York City

In New York City, the climate adaptation effort grew directly out of the release of the report *PlaNYC: A Greener, Greater New York*, which recommended the formation of an intergovernmental task force, a plan to protect communities at high risk from climate impacts, and an overall adaptation planning process. The following year, Mayor Bloomberg formed the Climate Change Adaptation Task Force to address infrastructure vulnerabilities and also the New York City Panel on Climate Change to function as a technical advisory committee on developing city-specific climate change projections and assist in new infrastructure standards. New York requires annual performance reports on established indicators. The Port Authority of New York and New Jersey has also been very active in addressing climate adaptation, by implementing guidance to consider the impacts of climate change, raising the flood plain elevation, and even implementing some strategies in projects.

Climate projections were downscaled to the New York City region by applying the projected changes from the relevant grid box to observed climate data. In addition, because there has been controversy over the IPCC 2007 sea-level rise predictions, which did not include melting of the Greenland and Antarctic ice sheets, the New York scenarios included an additional sea-level rise scenario that corresponded to more rapid ice melt. New York City's risk-based approach to adaptation, "Flexible Adaptation Pathways," is an iterative process that recognizes the multiple dimensions of climate hazards, impacts, adaptations, economic development, and other social factors. This iterative process is predicated on the establishment of climate change monitoring programs that can provide feedback to the process to allow for changing "pathways."

Most recently, in response to Hurricane Sandy (2012), New York Governor Mario Cuomo established several commissions to investigate the lessons learned from the massive devastation to infrastructure caused by the storm in New York City. The commission focusing on infrastructure predicted that the state would experience more frequent floods, storm surges, heat waves, and droughts. In preparation, the commission recommended that transportation infrastructure be designed to be more resilient to such environmental conditions and that better preparation occur in protecting existing infrastructure. New York City prepared a plan that outlined specific actions that should be taken to provide a more resilient infrastructure to future extreme weather events (New York City 2013).

Punta Gorda, Florida

The City of Punta Gorda, Florida, inserted an adaptation component into the city comprehensive plan as well as its Comprehensive Conservation and Management Plan in 2008. It has adopted comprehensive plan language to address the impacts of sea-level rise and seeks strategies to combat its effects on the shoreline of the city. Punta Gorda developed its adaptation plan in partnership with the U.S. Environmental Protection Agency (EPA), as part of EPA's Climate Ready Estuaries Program (Southwest Florida Regional Planning Council 2009).

The approach taken by the City of Punta Gorda, Florida, represents an advanced approach for a small city (no doubt in part because of its participation in EPA's Climate Ready Estuaries Program, which provided additional technical support). For the plan, critical facilities of all types were identified. For transportation, this consisted of a list of all bridges in the city; no other transportation facilities were singled out as critical facilities. Infrastructure costs, based on estimates prepared for a previous Federal Emergency Management Agency (FEMA) disaster preparedness plan, were used to estimate losses from storm flooding (based on the facility's location in flood zones). To assess risk and vulnerability of critical infrastructure to various climate effects, rather than conduct a quantitative engineering analysis of the infrastructure, Punta Gorda turned to a stakeholder and public involvement approach. At a series of public meetings, stakeholders and the public engaged in exercises to identify and prioritize areas of vulnerability and to recommend preferred adaptation strategies.

3.3 International Perspectives

Eleven adaptation studies from four countries (United Kingdom, Australia, Canada, and Norway) were reviewed for this project. These countries were chosen because they are considered leaders in climate change adaptation practice and they have extensive literature available in English. Before discussing the specific studies, it is useful to have an understanding of the different contexts in which the various plans were created. For three of the countries studied (Australia, Canada, and the United Kingdom), a brief summary of the national perspective overarching these plans is provided.

3.3.1 Overview of National Climate Change Policies

Australia

In Australia, mitigation and adaption are managed under the same government agency—the Department of Climate Change and Energy Efficiency. The government's climate change policy rests on three actions (Commonwealth of Australia 2010):

- Mitigation—reduce Australia's greenhouse gas emissions
- Adaptation—adapt to the climate change that cannot be avoided
- Global solution—help shape a collective international response

In its climate change white paper, the national government states that several principles will guide its efforts:

- Decisions that it makes today will affect its future vulnerability.
- Uncertainty is a reason for flexibility and creativity, not for delay.
- Businesses and the community must play their part.
- Governments have an important capacity-building and reform role.
- The roles of commonwealth, state, territory and local governments are different.

With respect to infrastructure, "significant current investments in infrastructure and its long lifespan make it essential to consider the impacts of climate change now to avoid locking in ineffective and inappropriate infrastructure and policies. The commonwealth has a key interest in ensuring the owners of nationally significant infrastructure (such as ports, roads, and infrastructure for water, electricity, and telecommunication services) provide continued and uninterrupted functioning of these assets, which are critical to supporting our national economy" (Commonwealth of Australia 2010).

Canada

In Canada, climate change does not appear to be the jurisdiction of a single agency. Climate change activities can be found on Environment Canada and Natural Resources Canada's websites, and the government of Canada also has a website devoted to climate change. On its website, it describes the following four investments it has made to help Canadians adapt to climate change and its impacts:

- Developing a pilot alert and response system to protect the health of Canadians from infectious disease
- Assessing key vulnerabilities and health impacts related to climate change in Northern/Inuit populations
- Improving predictions of climate changes in Canada
- Disseminating management tools for adaptation and supporting the development and implementation of regional adaptation programs

In addition, Natural Resources Canada through its Climate Change Impacts and Adaptation Division has funded more than 300 impacts and adaptation research projects, which have emphasized local decision-maker participation in addressing climate change impacts and adaptation.

United Kingdom

The Climate Change Act of 2008 made the United Kingdom the first country in the world to have a legally binding, long-term framework to cut carbon emissions. The act also created a framework for building the United Kingdom's ability to adapt to climate change. The Climate Change Act created a new approach to managing and responding to climate change in the United Kingdom by:

- Setting ambitious, legally binding targets;
- Taking powers to help meet those targets;
- Strengthening the institutional framework;
- Enhancing the United Kingdom's ability to adapt to the impact of climate change; and
- Establishing clear and regular accountability to the UK Parliament and to the devolved legislatures.

Key provisions of the act specific to adaptation are:

- A requirement for the government to report at least every 5 years on the risks to the United Kingdom of climate change and to publish a program setting out how these will be addressed;
- The introduction of powers for the government to require public bodies and statutory undertakers to carry out their own risk assessment and make plans to address those risks; and
- An Adaptation Subcommittee of the Committee on Climate Change, providing advice to, and scrutiny of, the government's adaptation work.

The United Kingdom has produced the Climate Change Risk Assessment (CCRA), which is the first-ever comprehensive assessment of potential risks and opportunities for the United Kingdom from climate change (Department for Environment, Food and Rural Affairs 2012). This represents a key part of the government's response to the Climate Change Act of 2008, which requires a series of assessments of climate risks to the United Kingdom. The CCRA includes a detailed analysis of over 100 climate impacts, on the basis of their likelihood, the scale of their potential consequences, and the urgency with which action may be needed to address them.

The CCRA classifies risks and opportunities into three broad impact classes—"low," "medium," and "high"—and also identifies those risks that are highly uncertain and difficult to quantify. In addition, projected ranges of possible climate outcomes are given across the three emission scenarios for each of the three future time periods. Potential climate impacts are discussed within these three timeframes: "the 2020s" (2010–2039), "the 2050s" (2040–2069), and "the 2080s" (2070–2099). The CCRA methodology has been developed through a number of stages involving expert peer review. The approach developed is a manageable, repeatable methodology between the 5-year cycles of the CCRA.

Confidence in a large number of the CCRA findings is generally low to medium, with only risks that are already being experienced and those related to increased temperatures classified as high. Several of the emerging risks examined are potentially very significant, but "current level of knowledge" means that there are also large uncertainties, especially with respect to potential climate impacts on ecosystems and business networks.

With regard to transportation impacts, increased winter rainfall and higher river flows may lead to more damage to road and rail bridges. Old masonry arch bridges are most at risk from "scouring," where their foundations can be washed away. Bridges can also be weakened during floods by the impact from floating debris (e.g., motor vehicles) and the washing-out of loose masonry and "fill" material resulting from poor bridge maintenance.

The Climate Change Act of 2008 places a requirement on the secretary of state to lay a program of actions before Parliament addressing the risks identified in the CCRA "as soon as reasonably practicable" after the CCRA. This program will be the first National Adaptation Program (NAP) covering a period of 5 years (2013–2018). The NAP will be reviewed and a new program developed on a 5-year cycle, following each new CCRA. The first NAP will focus on helping UK businesses, local authorities, and society to become more resilient or "climate ready" to climate change impacts.

3.3.2 International Adaptation Initiatives for the Transportation System

Australia

The Australian government's *Climate Change Impacts & Risk Management: A Guide for Business and Government* proposes a process for organizations to investigate the risks of climate change (Commonwealth of Australia 2006). It asks users of the guide to "identify those activities and assets that are at risk from a changing climate." The workshop-based process has participants "(1) consider (based on their professional knowledge) which activities and assets of the organization are sensitive to climate change and (2) form a judgment as to whether climate change is a significant source of risk to the assets and activities relative to other sources of risk" (p. 18). The first step in the workshop-based process begins before the workshop. It calls for all participants in the climate change risk management exercise to understand the context in which the evaluation will be occurring.

Establishing the context consists of five parts:

- Defining how the climate will be assumed to change in the future
- Defining the scope of the assessment including activities to be covered, geographic boundaries, and the time horizon
- Determining whose views need to be taken into account, who can contribute to the analysis, and who needs to know its outcomes
- Defining how risks will be evaluated by clarifying the objectives and success criteria for the organization and establishing scales for measuring consequences, likelihoods, and risk priorities
- Creating a framework that will assist in identifying risks by breaking down the organization's concerns into a number of areas of focus and relating them to the climate scenarios

The guide recognizes that for some issues there may be need for more detailed analysis (for reasons of needing to better understand the climate change itself, needing to better understand the impact of climate change on operations, or to better understand and evaluate the treatment options). The guide provides a brief overview of the above issues, but because the issues affecting individual organizations will be different it did not go into great detail. The guide concludes with information about how to prepare and plan for a climate change risk management workshop.

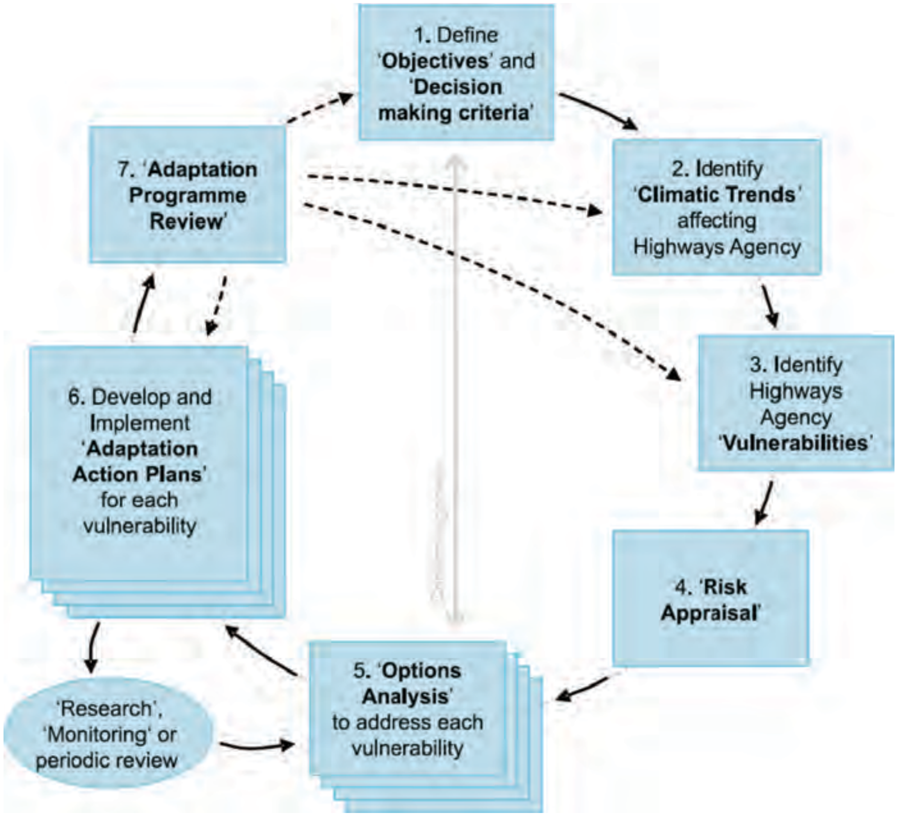
England

Perhaps the most fully developed adaptation framework is that described in the Highway Agency's *Climate Change Adaptation Strategy* (Highways Agency and Parsons-Brinckerhoff 2008). The Highways Agency Adaptation Strategy Model (HAASM), which is the focus of Volume 1 of *Climate Change Adaptation Strategy*, is a seven-step process for developing a climate change program. It provides a method for prioritizing risk and identifies staff members responsible for different climate change adaptation program development efforts. The other international reports reviewed do not provide such an inclusive look at climate change adaptation. Figure II.7 provides a graphic overview of the HAASM.

The HAASM model is one of the best examples of incorporating risk into its analysis. The following paragraphs explain the seven-stage process.

Stage 1: Define Objectives and Decision-Making Criteria. The first step of the HAASM is to define the objectives and decision-making criteria so that the model is aligned with the agency's mission. The objective was "to enable the Highways Agency to systematically develop and implement its responses to the challenges of climate change in support of the delivery of its corporate objectives" (Highways Agency and Parsons-Brinckerhoff 2008, p. 5). The decision-making criteria for selecting adaptation actions are in "accord with the Highways Agency's sustainability requirements and provide the optimum balance between minimum whole lifecost, certainty of risk, and residual risk" (p. 5).

Stage 2: Identify Climate Trends that Affect the Highways Agency. The second stage categorizes possible climate changes hazards into primary and secondary impacts based on their impacts on the Highways Agency's activities. The possible climate changes form the basis for identifying vulnerabilities in Stage 3.



Source: Highways Agency and Parsons-Brinkerhoff (2008).

Figure II.7. Highways Agency Adaptation Strategy Model.

Stage 3: Identify Highways Agency Vulnerabilities. Vulnerabilities are the Highways Agency activities that could be affected—positively or negatively—by climate change. They represent the ways the Agency may need to change its current practices in the future. The vulnerabilities are documented in a vulnerability schedule, which considers how climate change impacts could affect the delivery of the Highways Agency's corporate objectives.

Stage 4: Risk Appraisal. Stage 4 considers the climate change–associated risks as they relate to the vulnerabilities so that the Highways Agency can focus its climate change adaptation efforts to those activities that are most at risk. Four primary criteria are used in the risk appraisal: uncertainty, rate of climate change, extent of disruption, and severity of disruption.

The Highways Agency employs a methodical way of scoring vulnerabilities. Each vulnerability receives a high, medium, or low ranking for each of the primary risk appraisal criteria and the rankings are converted to numbers (3, 2, 1, respectively). Rather than create a single, composite score, the HAASM develops five scores reflecting different reasons for taking action.

Stage 5: Options Analysis to Address Vulnerabilities. Stage 5 establishes a preferred option for managing the risk associated with each of the vulnerabilities identified in Stage 3 and prioritized in Stage 4. In some cases, the preferred option will be apparent while others may require more detailed analysis. To determine the best option, the HAASM recommends that feasible options are considered, expected outcomes are determined, and costs and benefits are estimated. "The key requirement is for experts to consider carefully the sustainable options they consider have the potential to offer the minimum whole-life-cost, minimum risk, and greatest certainty of outcome" (Highways Agency and Parsons-Brinckerhoff 2008).

Stage 6: Develop and Implement Adaptation Action Plans. In Stage 6, detailed adaptation plans for each preferred option are developed. "Wherever possible, the adaptation action plans will define the steps necessary to modify existing Highways Agency Standards, Specifications, and other operating procedures, rather than lead to the development of new requirements. In some cases, they may determine that no immediate action is necessary, but instead a trigger for future review [is needed]" (Highways Agency and Parsons-Brinckerhoff 2008).

Stage 7: Adaptation Program Review. Stage 7 draws key information from the adaptation action plans into an overall adaptation program. A climate change program manager is responsible for implementation and oversight of the program and preparing an annual Climate Change Adaptation Progress Report. As part of Stage 7, it is expected that four feedback loops are completed. The model recommends that the process stages be revisited and information revised as needed based on the findings.

Scotland and Canada

Two other international reports of interest included the *Scottish Road Network Landslide Study: Implementation* and *The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada.* These followed a more technical approach for evaluating impacts. The studies were less concerned with setting up organizational protocols of risk management and more interested in testing climate change impacts on the landscape and infrastructure.

The *Scottish Road Network Landslide Study: Implementation* report focused on assessing and ranking the hazards presented by debris flow (Winter et al. 2008). The hazard assessment process involved "the GIS-based spatial determination of zones of susceptibility which are then related to the trunk road network by means of plausible flow paths to determine specific hazard locations. The approach taken, using a GIS-based assessment, enabled large volumes of data to be analyzed relatively quickly and was able to rapidly deliver a scientifically sound platform for the assessment. This desk-based approach to hazard assessment was then supplemented by site-specific inspections, including site walkovers, to give a hazard score for each site of interest. The subsequent hazard ranking process involved the development of exposure scores predicated primarily upon the risk to life and limb, but also taking some account of the socioeconomic impact of debris flow events. Finally, these scores were combined with the hazard scores to give site-specific scores for hazard ranking from which a listing of high hazard ranking sites in Scotland was produced" (Winter et al. 2008, p. 6).

The *Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada* used two different methodologies to test the impact of different climate change–related variables on pavement performance (Mills et al. 2007). The first set of case studies "examined deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure" (Mills et al. 2007, p. vii). The second set of case studies used the AASHTO *Mechanistic–Empirical Pavement Design Guide.* A series of analyses were conducted to test the (1) influence of climate and climate change alone, (2) influence of structure type and baseline traffic volume, and (3) combined influence of traffic growth and climate change. The study does not raise significant concern over the impacts of climate change on pavement performance. However, it did foresee that secondary and tertiary roads (with weak pavement structures and excessive traffic loads) will experience more impacts associated with climate change (p. 68).

3.4 Diagnostic Framework

A diagnostic framework provides highway agency staff with a general step-by-step approach for assessing climate change impacts and deciding on a course of action. A framework can be applied from the systems planning level down to the scale of individual projects. The framework described in this section was tested in three states and modified based on feedback from state DOT officials. A more detailed description of the diagnostic framework is found in Part I, the Practitioner's Guide, that was developed as part of this research. This section will present only a summary of the key steps in the framework.

The diagnostic framework is shown in Figure II.8. The following paragraphs summarize the key steps in this framework.

Step 1: Identify Key Goals and Performance Measures

The diagnostic framework begins with identifying what is really important to the agency or jurisdiction concerning potential disruption to the transportation system or facilities. At a high level, this includes goals and objectives. At a systems management level, this includes performance measures. Thus, for example, goals and performance measures could reflect economic impacts, disruptions of passenger and freight flows, harmful environmental impacts, etc. In the context of adaptation, an agency might be mostly concerned with protecting those assets that handle the most critical flows of passengers and goods through its jurisdiction, such as interstate highways, airports, or port terminals. Or, in the context of extreme weather events, it might focus on roads that serve as major evacuation routes and/or roads that will likely serve as routes serving recovery efforts. Or, focus might be given to routes and services that will provide access to emergency management and medical facilities. It is important that these measures be identified early in the process because they influence the type of information produced and data collected as part of the adaptation process. They feed directly into the next phase, defining policies that will focus agency attention on identified transportation assets.

Step 2: Define Policies on Assets, Asset Types, or Locations that Will Receive Adaptation Consideration

Changes in climate can affect many different components of a transportation system. Depending on the type of hazard or

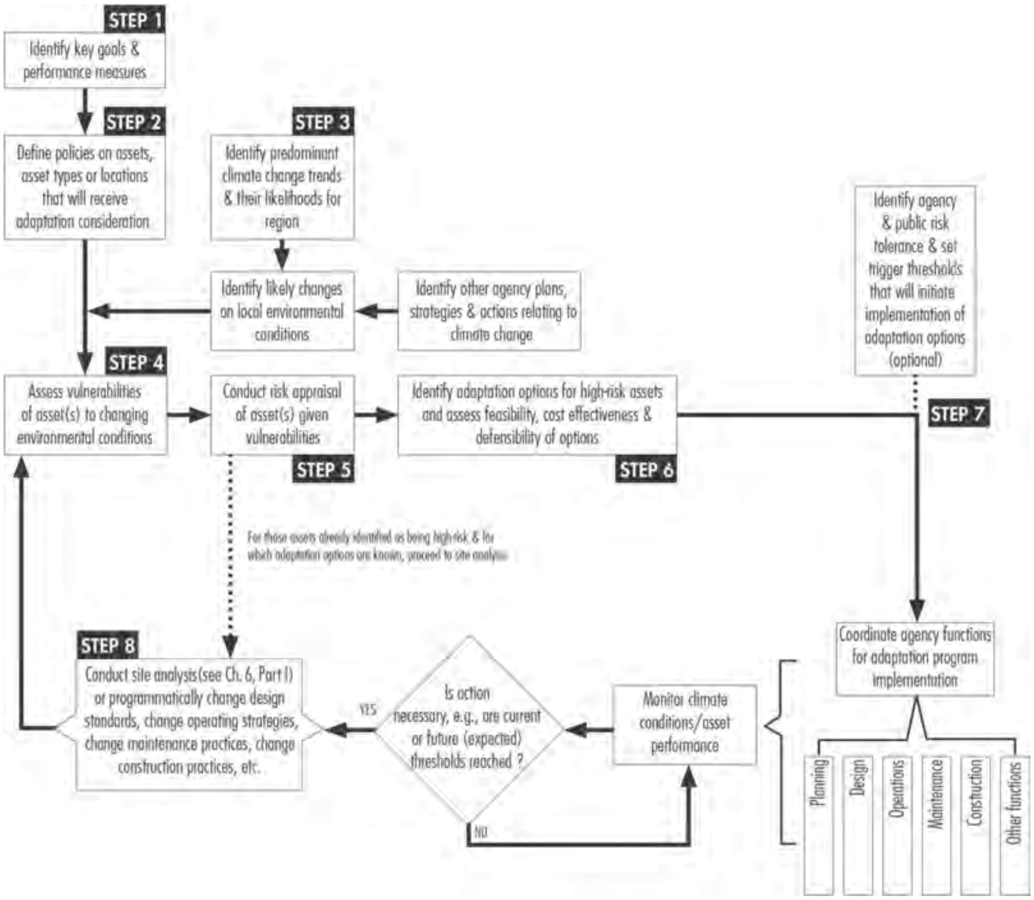


Figure II.8. Adaptation Assessment Diagnostic Framework threat, the impact to the integrity and resiliency of the system will vary. Given limited resources and thus a constrained capacity to modify an entire network, some agencies might choose to establish policies that limit their analysis to only those assets that are critical to network performance or are important in achieving other objectives (e.g., protecting strategic economic resources, such as major employment centers, industrial areas, etc.). Or, because of historical experience with weather-related disruptions, the agency might choose to focus its attentions on critical locations where weather-related disruptions are expected. These objectives follow directly from Step 1.

If an agency wants to conduct a systematic process for identifying the most critical assets, the criteria for identifying the assets, asset types, or important locations might include (1) high-volume flows, (2) linkage to important centers such as military bases or intermodal terminals, (3) serving highly vulnerable populations, (4) functioning as emergency response or evacuation routes, (5) condition (e.g., older assets might be more vulnerable than newer ones), and (6) having an important role in the connectivity of the national or state transportation network. However, agencies may not want to look at only critical assets because of the potential to miss "big issues" that were unforeseen elsewhere on the network and the political difficulty in saying some areas will be considered and others will not. This was one of the conclusions of the FHWA pilot case studies mentioned earlier.

Step 3: Identify Climate Changes and Effects on Local Environmental Conditions

Step 3 identifies over the long term those changes in climate and the corresponding changes in local environmental conditions that could affect transportation design and operation. To identify climate changes and the effects on local environmental conditions, transportation officials will need to review updated regional and local climate modeling studies—or at the very least deduce local impacts from national and global climate studies. It is important to note that the current state of the practice of climate modeling varies by type of variable being forecast (e.g., increase in temperature is highly likely while there is a lot of uncertainty on regional changes in precipitation) and by change in the type of local weather condition (e.g., most models forecast more intense thunderstorms but there is very little consensus on whether there will be more tornados). Officials thus need to consider such information as being the best current science can produce with respect to transportation adaptation studies.

The United States Geological Survey has produced a GIS-based website hosting downscaled climate data, i.e., data at more disaggregate levels, that reflect changes in average climatic conditions as well as in extreme values (see Chapter 3). In addition, the private vendor ClimSystems sells a software tool called SimClim™ that provides downscaled climate data for much of the U.S. and world.

Step 4: Identify the Vulnerabilities of Asset(s) to Changing Environmental Conditions

Step 4 matches the results of the previous two steps and assesses how vulnerable the targeted assets are likely to be to changes in local environmental and weather conditions. This assessment might entail, for example, examining potential flooding and the ability of drainage systems to handle greater flow demands or the likelihood of some segments of a facility being inundated with more frequent and severe storms. The vulnerability assessment might involve engineering analyses of the asset and the likelihood of different asset elements failing due to environmental factors.

Step 5: Conduct Risk Appraisal of Asset(s) Given Vulnerabilities

Risk appraisal, at a minimum, considers the likelihood of the climate change occurring and causing asset failure along with some characterization of the consequences of that failure (in terms of system performance, damage costs, safety risks, etc.). England's Highways Agency and Parsons-Brinckerhoff (2008), for example, developed a risk appraisal process based on the following four elements:

- "*Uncertainty*—compound measure of current uncertainty in climate change predictions and the effects of climate change on the asset/activity."
- "*Rate of climate change*—measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity."
- "*Extent of disruption*—measure taking account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important if it affects a high proportion of the network, or a small number of highly strategic points on the network."
- "*Severity of disruption*—measure of the recovery time in the event of a climate-related event (e.g., flood or landslip). This is separate from 'how bad' the actual event is when it occurs, e.g., how many running lanes [are lost]; it focuses on how easy/difficult it is to recover from the event, i.e., how long it takes to get those running lanes back into use."

The uncertainty and rate of climate change considerations provide a qualitative characterization of likelihood whereas the extent and severity of disruption elements characterize consequence.

Step 6: Identify Adaptation Options for High-Risk Assets and Assess Feasibility, Cost Effectiveness, and Defensibility of Options

Identifying and assessing appropriate strategies for the challenges facing critical infrastructure assets is a core component of the process shown in Figure 8. Such strategies might include modifying operations and maintenance practices (such as developing and signing detour routes around areas at a heightened risk of road closure), designing extra redundancy into a project, providing above-normal reserve capacity, incorporating a greater sensitivity to the protection of critical elements of the project design (such as better protection against bridge scour or high winds), designing with different design standards that reflect changing conditions (such as higher bridge clearances for storm surges), or planning for more frequent disruptions. In particular with respect to design standards, a more robust approach could be adopted that takes into account risk and uncertainty.

In many ways, considering climate-induced changes in the design process follows a model that has been applied in earthquake engineering. Building codes and design standards have been changed to reflect the forces that will be applied to a structure during a seismic event. Substantial research on the response of materials, soils, and structures themselves has led to a better understanding of the factors that can be incorporated into engineering design to account for such extreme events. Similarly, other design contexts reflect forces that might be applied during collisions, fires, or heavy snows. The logical approach for considering the best design for climate-induced changes is to examine the relationship among the many different design contexts that a structure might be facing and determine which one "controls" the ultimate design.

Step 7: Coordinate Agency Functions for Adaptation Program Implementation (and optionally identify agency/public risk tolerance and set trigger thresholds)

This step in the diagnostic framework identifies which agency functions will be affected the most by changes in infrastructure management practices. Given the range of climate stressors and extreme weather events that states might face, it is likely that many of an agency's functional units—planning, project development, operations, construction, and maintenance—will have some role to play in developing a strategy. Furthermore, it is reasonable to expect that the new challenges imposed upon transportation infrastructure managers by climate change will require new adaptive efforts that are dependent upon interagency cooperation. For example, an analysis of the impact of riverine flooding on transportation and other infrastructures may determine that the most cost-effective adaptation will involve a combination of bridge design adjustments and river channel widening, thus necessitating coordination between the transportation agency and the USACE. Planning for failures (e.g., prepositioning replacement materials in highly vulnerable locations) is important too and may be needed more with increasing frequency and intensity of extreme weather events.

Many of the changes in climate considered as part of this assessment will likely not occur for decades, and it is also likely that the full extent of the estimated impacts of such changes on transportation facilities or systems may not occur until even further into the future. An agency might want to establish "trigger" thresholds that serve as an early warning system so that agency officials can examine alternative ways of designing, constructing, operating, and maintaining transportation infrastructure in response to higher likelihoods of changed environmental conditions.

The adaptive systems management approach is foremost an iterative process. Realization of the intended benefits of this approach (minimization of risk and development of cost-effective adaptation strategies) requires that the latest information on changing environmental conditions and system performance priorities be incorporated into the process through monitoring external conditions and asset performance/condition, either in an asset management system or through some other means.

Step 8: Conduct Site Analysis or Modify Design Standards, Operating Strategies, Maintenance Strategies, Construction Practices, etc.

When a decision is made to take action, the agency should implement whatever cost-effective strategies seem most appropriate. As shown in Figure II.8, this could range from changes in design procedures to changes in construction practices. If the focus of the adaptation assessment is on specific assets in a particular location, more detailed engineering site analyses might be needed.

Once such actions are implemented, the adaptation assessment process links back to identifying vulnerabilities. Given that the agency has now changed the status or condition of a particular asset, at some point in the future it might be necessary to determine yet again what future vulnerabilities might occur given this new condition.

As noted earlier, Part I, Practitioner's Guide, provides a far greater level of detail on the application of this diagnostic framework in different contexts.

CHAPTER 4

Context for Adaptation Assessment

4.1 Introduction

The impact that climate change could have on the future transportation system depends on both the changes to society and the transportation system that supports it, and the magnitude and nature of the climate changes that will take place. This chapter provides an overview of potential demographic, land use, and transportation system changes in coming years, and projections for key climate change drivers based on up-to-date climate modeling.

4.2 Potential Demographic, Land Use, and Transportation System Changes in the United States by 2050

Because climate change occurs over decades, developing sound adaptation strategies requires a long-term perspective. Transportation officials need to consider not only the existing highway infrastructure—which in many cases will be in service for 50 or more years—but also how transportation networks may change over time and how climate impacts and adaptation may need to be integrated into future changes to the highway system. Shifts in demographic trends, land use patterns, and advances in transportation technology over the next few decades will have profound impacts on how the highway system functions, its design, and its spatial extent. As transportation officials shape the future highway system to address new demands, a consideration of future climate conditions should be considered as part of the planning and decision-making process. The following summary provides an overview of broad national trends in demographics, land use, and transportation systems that have the potential to influence how the future highway system could be used, thus reflecting the impacts that climate change could have on transportation systems and on the economic and social benefits associated with system use.

4.2.1 Population and Demographics

The United States will continue to grow. By mid-century, population is projected to reach just under 400 million people (Bureau of the Census 2012). This growth in U.S. population is projected to be concentrated in specific areas of the country. Between now and 2050, most population growth is expected to occur in the southern and western regions of the United States. Growth rates are anticipated to be particularly high in coastal counties across the country, especially in the Southeast. This growth pattern is particularly important for adaptation planning, as increasing coastal populations provide higher population exposure to serious effects of changing climate conditions, including rising sea levels and, on the East and Gulf Coasts, more intense hurricanes. If this development and population growth pattern continues, special attention will need to be devoted to ensuring housing and infrastructure investments in these locations are resilient to these impacts. Also, precipitation in the southwestern United States, one of the nation's projected growth areas, is likely to decrease in future decades as the result of climate change, thus creating significant challenges with providing the water that is necessary to support urban populations (Christensen et al. 2007).

In addition to the expected growth in the Southeast and West, some researchers have noted another spatial trend that could become more pronounced in the future—the formation of megaregions. Megaregions are defined as large interconnected networks of metropolitan centers (often consisting of many states) linked by transportation infrastructure. Considering urbanization on this scale captures the political, economic, and spatial levels at which some believe planning should address the challenges of agglomerations of economic activity and population (Ross 2009). According to Carbonell and Yaro (2005), more than one-half of the future population and about two-thirds of the economic growth will occur within eight megaregion areas through 2050. The Gulf Coast and Florida/Peninsula megaregions, two of the eight, have particularly high vulnerabilities to projected sea-level rises and potential changes to hurricane intensity and frequency.

Similar to other western nations, the U.S. population is aging. The Census Bureau projects that U.S. population in 2050 will consist of over 88 million people aged 65 years or older, comprising about 20 percent of the future population (Bernstein and Edwards 2008). This group will include the 19 million people in the "baby boomer" generation, who will be 85 years of age or older. The elderly, in particular the impoverished elderly, are an especially vulnerable group to projected climate change impacts such as longer and hotter heat waves and more intense storms.

4.2.2 Land Use

The demographic factors described above—including the large wave of baby boomers set to retire, increased immigration, new land use policies, and shifting market demand—will influence the types and locations of developments. Housing development could experience a dramatic surge by mid-century. According to a TRB study, most of the housing for the nation's future population growth and replacement housing has yet to be built (Committee for the Study on Relationships among Development Patterns, Vehicle Miles Traveled, and Energy Consumption 2009). In fact, up to 105 million additional housing units may need to be built by 2050 to meet demand—nearly doubling the 2000 housing stock. The increase in housing units assumes new or replacement housing due to the difficulty of converting the existing housing stock to higher-density units.

Some professionals in the transportation planning and real estate industries believe that the future will bring a shift toward more compact development in urbanized areas (Cowden 2009). Evidence seems to suggest that there is currently an imbalance between the demand for compact housing and its supply. According to the report, 35 percent of potential residents want walkable communities, while only 2 percent of existing communities meet these characteristics.

On the other hand, there is still some skepticism that land use patterns will change dramatically. Some believe low-density "sprawl" development patterns will likely continue to be common practice once market conditions improve. For example, the TRB report mentioned earlier, written by an expert committee assembled to investigate the impacts of compact development on driving, noted disagreement among committee members on the scale to which compact development could occur by 2050. Committee members skeptical of a large-scale shift toward compact development cited the inertia of existing housing trends, entrenched low-density land use policies, and established housing preferences as reasons for their pessimism (Committee for the Study on Relationships among Development Patterns, Vehicle Miles Traveled, and Energy Consumption 2009).

Although future development patterns are difficult to predict, the literature suggests that there will be a very large demand for new development over the next 50 years, and where this development locates and what form it takes will have an influence on the location and types of transportation capacity improvements that will be necessary.

4.2.3 Potential Changes to Transportation Systems and Technology

Similar to the difficulty in predicting future land use patterns, expectations of what the future highway system will look like vary widely, often depending on the level of investment that is assumed in the system. Many large-scale rehabilitation or reconstruction efforts likely will take place over the next half-century. AASHTO notes that many existing roadways are too old to be subjected to the same re-surfacing practices that have been in place since their construction and that total reconstruction will likely be necessary (AASHTO 2010). Additionally AASHTO states that one of the more important future highway system needs will be the likely rehabilitation or replacement of many of the Interstate system's 55,000 bridges and 15,000 interchanges, pending findings from a recommended needs assessment of the Interstate system. Technologies related to "smart" sensors, more durable materials, and low-weight, high-strength composites could also be in widespread use in the 2030 to 2050 timeframe.

If such efforts are made, it would represent a remarkable opportunity to incorporate climate change adaptation measures into the upgrade of the nation's major highway system. Given what was described earlier as being the areas of growth in population in the United States in the next several decades, it seems likely that much of the pressure for network expansion will be in these same areas. As was also noted, these areas are also likely to be prone to some of the most dramatic changes in climate facing the United States. Thus, there will likely be some real opportunities to consider seriously where this new infrastructure will be placed and how it will be built.

With respect to system operations, both government and private companies have been working to improve the delivery of real-time traffic information (e.g., Google Maps, Traffic.com) to drivers so that they are able to make better informed decisions and avoid congestion. Many municipalities already have started improving the delivery of traffic information through electronic signs erected over roadways, roadway information phone lines, or local radio stations. The increasing provision of up-to-date road condition information will be helpful as severe weather events—expected to increase in response to climate change—may render some links in the road network impassable necessitating quick plotting of alternate routes. This was exactly what happened in Vermont in response to Topical Storm Irene.

In summary, five major "contextual" messages have been identified in this research that relate to how socioeconomic and transportation system characteristics could affect the magnitude and direction of climate change impacts on the transportation system:

- *Message 1:* The U.S. population will continue to grow, with most of this growth occurring in urban areas and in parts of the country expecting notable changes in climate.
- *Message 2:* The composition of this population will be very different than it is today, with more diverse populations and elderly in the nation's population mix.
- *Message 3:* Significant levels of housing and corresponding development will be necessary to provide places to live and work for this population, with much of this development likely to occur in areas subject to changing environmental conditions.
- *Message 4:* Increasing population growth will create new demands for transportation infrastructure and services, once again in areas that are vulnerable to changing climate conditions.
- *Message 5:* The nation's highway system will be facing increasing demands for reconstruction and rehabilitation over the next 40 years (to 2050), which provides an opportunity to incorporate climate adaptation strategies into such efforts, if appropriate.

4.3 Expected Changes in Climate

Climate change projections are a product of assumptions about future greenhouse gas (GHG) emissions and how the atmosphere and climate responds to those emissions. This research analyzed a wide range of possible changes in climate, including two high-GHG-emissions scenarios, a middle-emissions scenario, and a low-emissions scenario. The emissions scenarios, shown in Table II.2, were developed by the IPCC in *Emissions Scenarios* [also known as the Special Report on Emissions Scenarios (SRES); Nakicenovic et al. 2000]. The two highest-emissions scenarios, A1FI and A2, were used for a "high-emissions scenario" and B1 was used as a "low-emissions scenario" in this research.

The best available information on how global climate will change in the future comes from general circulation models (GCMs), which divide the world into grid cells that are typically one hundred to a few hundred miles across. These models provide some insight into potential changes in climate at this scale. But with such large grids, important climate processes such as thunderstorms and the local effects of mountains and coastlines are unresolved or modeled via simplified processes. In general, the GCMs simulate large geographic areas and timescales better than smaller geographic areas and timescales. Also, the models tend to simulate temperature better than precipitation, although precipitation is better modeled over large geographic areas than small areas. The models also simulate annual changes better than seasonal changes, and seasonal changes better than monthly changes. (Those interested in knowing more about climate change modeling are referred to Part I, Practitioner's Guide.)

This research divided the United States and Puerto Rico into 11 regions (see Figures II.9 and II.10). These regions were selected to capture important regional differences in climate change projections. Projected climate changes within each region are similar but distinct from changes in adjacent regions. It was also desired to make the regions consistent with those

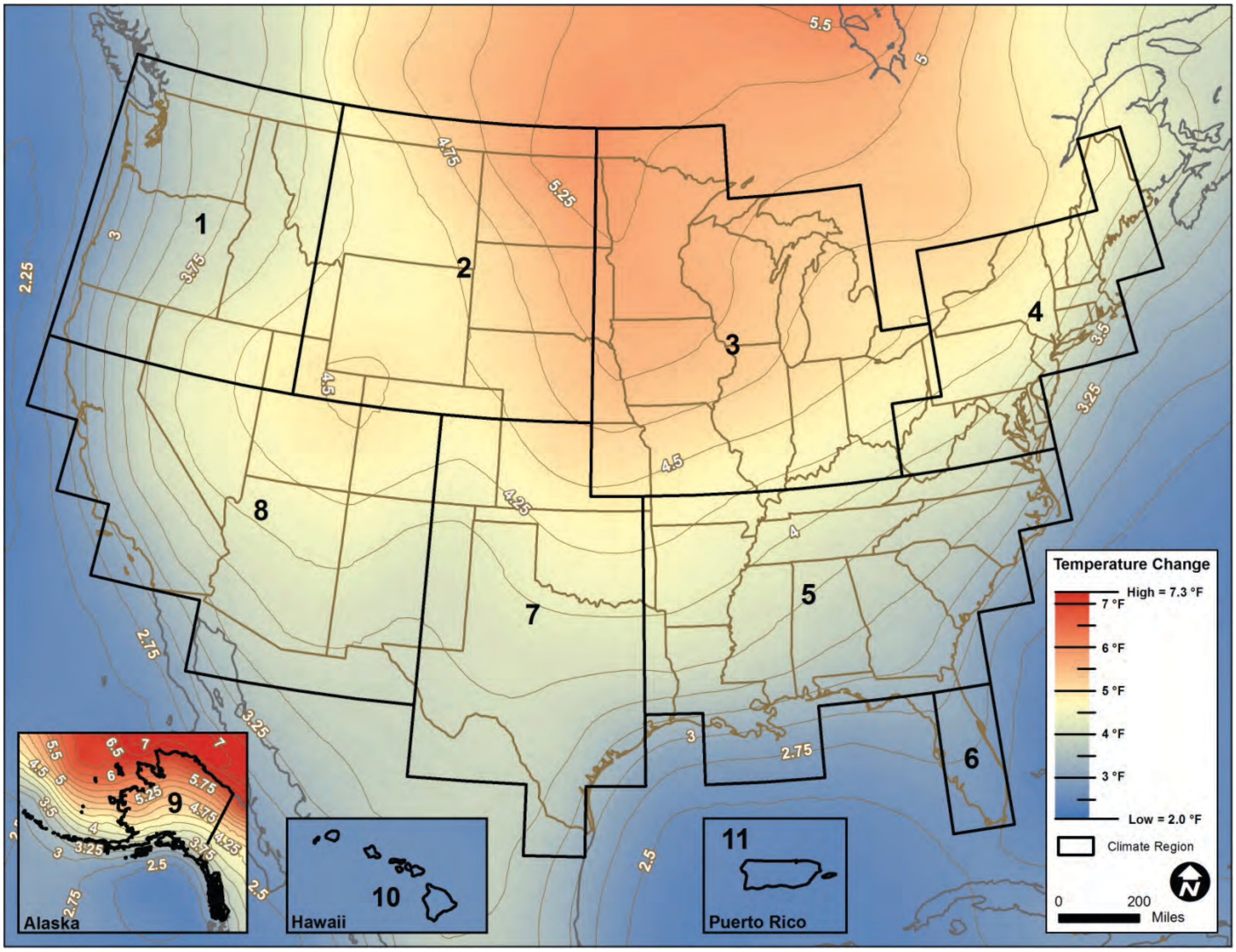
Table II.2. Scenario characteristics from the IPCC Special Report on Emissions Scenarios.

SRES Scenario	Key Assumptions	CO_2 Concentration in 2050 (ppm)*	Projected Increase in GMT from 2010 to 2050 (°F)
A1FI	Very high rates of growth in global income, moderate population growth, and very high fossil fuel use	570	2.7
A2	Moderate rates of economic growth, but very high rates of population growth	533	2.0
A1B	Same economic and population assumptions as the A1FI scenario, but assumes more use of low-carbon-emitting power sources and clean technologies	533	2.2
B1	Same population growth as A1FI and A1B, but assumes a more service-oriented economy and much more use of low-carbon-emitting power sources and clean technologies	487	1.5

* Carbon dioxide (CO_2) concentrations are currently over 390 ppm (having been approximately 280 ppm before the beginning of the Industrial Revolution), and global temperatures rose 0.74°C (1.3°F) between 1905 and 2005 (Earth System Research Laboratory 2012; Solomon et al. 2007).

GMT = global mean temperature

Source: Nakićenovic et al. (2000).



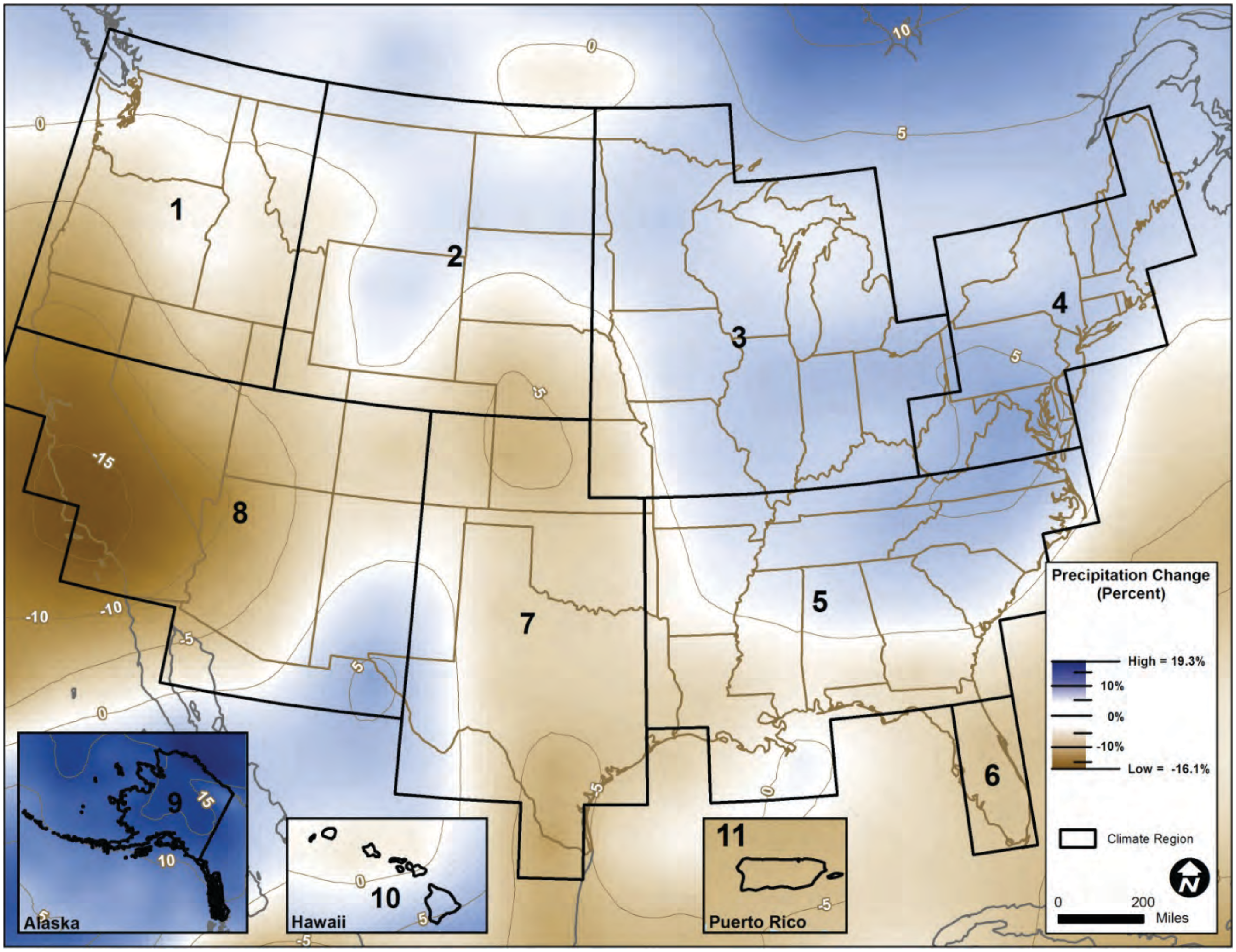
Note: This figure presents change in temperature across the United States. It is based on output from MAGICC/SCENGEN, which reports data in 2.5 degree grid boxes. Each grid box is approximately 150 miles across and contains an average change in temperature and precipitation for the entire grid box. The data are interpolated and smoothed to make them more presentable. Since the data are smoothed, transitions between different changes in temperature (and precipitation) should not be taken as being exact model output.

Figure II.9. Estimated increases in temperature (°F) in 2050 relative to 2010 using A1FI scenario, 3°C (5°F) sensitivity.

used by the FHWA and other federal agencies (ICF International 2009). With two significant exceptions, the eight continental regions are similar but not identical to those in the FHWA analysis, primarily because the regions need to align with the grid boxes used by the climate model applied in this research. One exception is the Great Plains region, which runs from the Canadian to the Mexican borders. The modeling for this research suggested differences in the magnitude of temperature increases and precipitation, as well as extreme event patterns between the northern and southern Great Plains. The region was split into the "Upper Great Plains" and "South Central" regions. Grid boxes that contained U.S. territories as well as oceans and parts of Canada or Mexico were included in coastal and border areas.

Florida was the second exception. In other grid systems Florida is included in the Southeast region. However, given that climate models tend to project decreased precipitation in Florida, whereas they tend to project slightly increased precipitation in the rest of the Southeast, it was determined that Florida deserved to be its own zone. Changes in annual, winter, and summer temperatures and precipitation from 2010 to 2050 were estimated for these regions as well as Alaska, Hawaii, and Puerto Rico.

Average temperature and precipitation projections were developed using MAGICC/SCENGEN (M/S), which contains parameterized outputs from 20 GCMs (Wigley 2008). Typically, GCMs are expensive to run and are run only for a limited number of scenarios. M/S uses parameterized regional outputs



Note: This figure presents change in precipitation across the United States. It is based on output from MAGICC/SCENGEN, which reports data in 2.5 degree grid boxes. Each grid box is approximately 150 miles across and contains an average change in temperature and precipitation for the entire grid box. The data are interpolated and smoothed to make them more presentable. Since the data are smoothed, transitions between different changes in precipitation (and temperature) should not be taken as being exact model output.

Figure II.10. Estimated percentage change in summer precipitation in 2050 relative to 2010 using A1FI scenario, 3°C (5°F) sensitivity.

from the GCMs to estimate climate changes quickly for GHG emissions scenarios, as well as other parameters for any region of the world. It is generally considered better to use multiple GCM outputs rather than a single model because the range of results across an array of models gives a better indication of possible changes in climate than a single model or even an average of models (Barsugli et al. 2009). This analysis used 10 of the 20 climate models that best simulate the current U.S. climate using the A1FI emissions scenario (Wigley 2008). These models gave a range of projected climate changes, particularly at the regional scale. A more detailed description of the M/S model used in this research is found in Appendix A.

Figures II.9 and II.10 show the projected changes in average temperature and average precipitation across the 10 GCMs for all of the regions. Appendix B presents the results of the analysis using so-called whisker diagrams. The composite figures give an indication of how projections can vary within and across regions, while the box-and-whisker diagrams show how projections in each region can vary across models.

Both types of information are useful. For example, Figure II.10 on summer precipitation changes shows some areas in Region 2 (Upper Great Plains) having a slight increase in precipitation and some having a slight decrease. In contrast, the box-and-whisker diagram for Region 2 (Figure II.11) shows that median annual precipitation change is close to zero and the

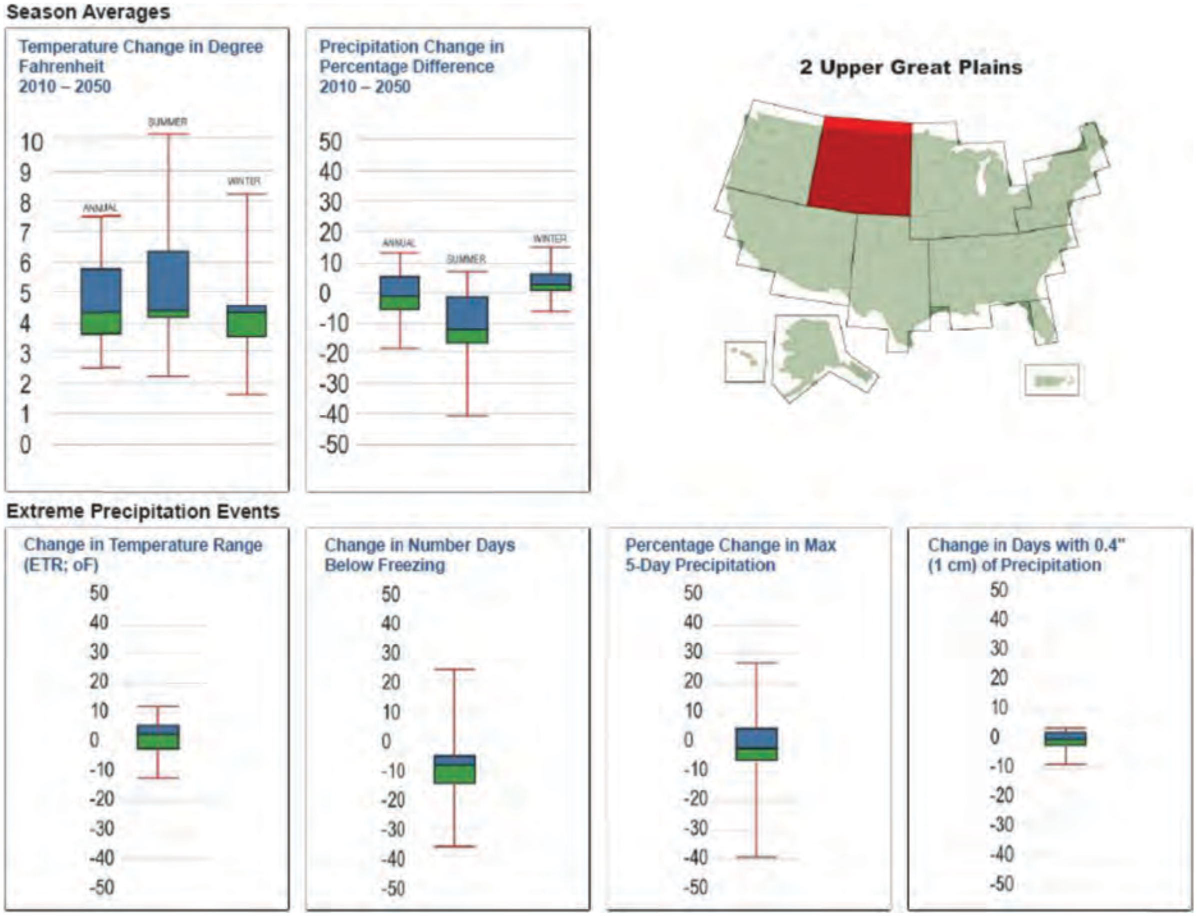


Figure II.11. Box-and-whisker diagram for Region 2.

box (which captures the 25th and 75th percentiles) is almost equally above and below zero. The whiskers have a much wider range. In total, Figure II.10 suggests that on average, northern areas in Region 2 are more likely to have relatively more precipitation than southern parts of the region. The box-and-whisker diagram, however, indicates that it is uncertain as to whether total precipitation across the region will increase or decrease.

Scenarios of climate change should consider increases and decreases in precipitation. In general, the amount of relative increase in precipitation could be slightly higher in northern areas than in southern parts of the region.

4.3.1 Average Temperature Projections

This section first presents projections of annual temperature change followed by projections of winter and summer temperature change by 2050.

Annual Temperatures

Increased GHG emissions are projected to result in increased temperatures across the United States. Assuming emissions follow the A1FI emissions scenario with a climate sensitivity of 3.0°C, temperatures in the lower 48 states are projected to increase about 4°F (2.3°C) by 2050 relative to 2010. [It is interesting to note that in the last 50 years, average U.S. temperatures, including Alaska, increased 2°F (Karl et al. 2009).] While all U.S. regions are projected to increase significantly in temperature, the amounts will vary by location and season. In general, areas farther inland will be warmer than coastal areas, because the relatively cooler oceans will moderate the warming over coastal lands. In addition, northern areas will warm more than southern areas. Snow and ice reflect sunlight and lead to cooler temperatures, whereas exposed land absorbs sunlight, which allows for a more rapid temperature increase. As the snow and ice cover decreases with higher temperatures, there will be more warming in such areas.

All of the climate model projections show increased temperatures under all scenarios in all regions. More warming is projected for northern and interior regions in the lower 48 states than for coastal and southern regions. As can be seen in Figure II.9, the range of model projections is quite wide. Thus, while there is agreement among the models that temperatures will rise over the first half of the 21st century (and beyond), there is significant uncertainty about the magnitude. (Note again that the projected changes in temperature would be lower with a lower GHG emissions scenario.)

Winter and Summer Temperatures

Seasonal changes will vary from the average annual changes, and this variation will have important consequences for the transportation system. Appendix B displays projected changes in average winter and summer temperatures for the 11 regions. The average model changes for winter in the contiguous 48 states are slightly lower than the average annual changes, but not in all regions. This may be because the models tend to project increased precipitation in winter, which can dampen the increase in temperatures.

As with annual temperatures, projected changes in seasonal temperatures are wide ranging, although the range from the 25th to 75th percentiles is much narrower. Based on this, it is reasonable to conclude that it is highly likely that winter temperatures will increase, but that the magnitude of warming is quite uncertain. None of the models project a decrease in summer temperatures, and thus it is not surprising that the average projected summer increases are generally higher than the average annual temperature increases. The relatively higher warming projected in summer with respect to winter may be the result of the models estimating a decrease or no change in summer precipitation in most regions (see below). Drier conditions result in more of the sun's energy heating the atmosphere rather than evaporating moisture.

4.3.2 Precipitation Projections

Annual Precipitation

On average, global precipitation is projected to increase. As the atmosphere warms, it holds more water vapor, causing more precipitation; however, this does not mean that average precipitation will increase everywhere (more intense precipitation, an important design consideration, might however). Under A1FI with a 3°C climate sensitivity, the models project little change in annual precipitation by 2050 when averaged over the United States, but do show substantial precipitation changes when examined by different regions (see Appendix B). Over the last 50 years, average precipitation over the United States increased by 5 percent (Karl et al. 2009).

As with temperatures, precipitation changes on average will vary by season and location (Solomon et al. 2007). Unlike the temperature projections, with one exception, the models do not show consistent projections of whether precipitation will increase or decrease by region. All but one region's model project significant increases and decreases in precipitation; the exception being Alaska, where all of the models project an increase in annual precipitation.

On average in the contiguous 48 states, the models project slightly increased precipitation in eastern regions and drier conditions in western and south central regions, the Deep South, and Florida, with the largest average precipitation increase estimated for the Northeast, and the largest decrease projected for the Southwest. In the Southwest, the entire box (see Appendix B) displaying the 25th to 75th percentiles of change in annual precipitation is below zero, showing that most models project a decrease in annual precipitation for the region. Alaska and Hawaii have even larger projected precipitation increases. These results conform to the IPCC estimates that average precipitation will likely increase in the Northeast and decrease in the Southwest, and that average precipitation will likely increase in Alaska and Hawaii, and decrease in the Caribbean in the summer (Christensen et al. 2007). "Likely" is defined by the IPCC as having more than a two out of three chance of being correct. In general, increasing average precipitation can be expected the farther northeast one heads, but where the transition from drier to wetter will occur is uncertain. So while it appears likely that the Northeast will have more average precipitation and the Southwest less, changes in other regions in the contiguous 48 states are less certain.

In contrast, Alaska and Hawaii are projected to have larger increases in annual precipitation, while Puerto Rico is projected to have a substantial decrease. The projection ranges for Hawaii and Puerto Rico are quite large relative to the average change.

Winter and Summer Precipitation

Generally, there is limited certainty in projected changes in summer precipitation. For most regions, the relatively low magnitude of average change compared to the wide range of projections and the disagreement among the 10 models about whether precipitation will increase or decrease suggests that the direction of change is uncertain. In general, there is a tendency for wetter winters in the northern and eastern areas and drier winters in the southern and western regions. Alaska is projected to be much wetter (all of the models except one project an increase in precipitation in Alaska).

As with the projected changes in winter precipitation, it is uncertain whether summer precipitation will increase or decrease in most regions. The strongest exception is, once again, Alaska where all the models project an increase in summer precipitation. In four regions—the Northwest, Upper Great Plains, Florida, and Puerto Rico—the 25th to 75th percentiles project decreased summer precipitation. Because of the GCMs' difficulty in simulating convective rain events (e.g., thunderstorms), the model projections for change in summer precipitation, particularly for projections for the contiguous 48 states, should not be accorded too much weight.

Even with the uncertainties associated with the model projections, the models tend to suggest *relatively* wetter winters and *relatively* drier summers. Note that higher temperatures will increase water evaporation and consumption by vegetation (transpiration). This transpiration could add to reduced summer runoff in many regions.

4.3.3 Changes in Extreme Events

Typically, the quantitative climate change projections presented by the IPCC estimate changes in average annual, average seasonal, or average monthly temperature or precipitation. Extreme event projections, such as intense precipitation and/or temperature, are not provided. One notable exception is the number of days exceeding a temperature threshold such as 90°F (32°C) (e.g., Karl et al. 2009). For many aspects of transportation infrastructure design and construction, extreme weather event changes may be more important than average condition changes (Meyer et al. 2012a; 2012b). The number of frost days, temperature fluctuations, temperatures exceeding certain thresholds, and high river flow events often determine the design criteria for bridges and roads.

One important exception to the lack of quantification of change in extreme events is the seminal article published by Tebaldi et al. (2006), which examined GCM estimates of changes in 10 extreme events on a regional basis. Given that Tebaldi et al. (2006) estimated changes in extremes from GCMs that were based on large grid boxes (roughly 1 degree to 4 degrees of latitude or longitude), simulating precipitation for convective events such as thunderstorms, which occur at a much smaller scale, became a significant challenge. Changes in temperature behave more uniformly but will still not capture local phenomena such as the influence of water bodies or mountains.

The following four events are particularly important for transportation:

- Intra-annual extreme temperature range, defined as the difference between the highest temperature of the year and the lowest
- Total number of frost days, defined as the annual total number of days with absolute minimum temperature below 32°F (0°C)
- Number of days with precipitation greater than 0.4 inches (10 millimeters)
- Maximum 5-day precipitation total

The difference between ***the highest and lowest temperatures*** in a year suggests more extreme heat and possibly extreme cold (although it could be that the highest temperature increases more than the lowest temperature). An increase in the range is projected for most regions. The average estimated changes range from a slight decrease in Florida to a 5°F (3°C) increase in the Southeast; however, only the average changes in the Southeast and South Central regions exceed the standard deviation across the models. The changes are relatively small when compared to the average model estimate of the current range in 2010. All regions have minimum and maximum changes that, in absolute terms, exceed the value of the average change.

Changes in frost days appear to be significant. Most of the regions are projected to have decreases of one to more than three weeks in the number of days with temperatures below freezing. The largest reductions are projected for the northern regions. Florida has virtually no days with this condition, but the climate models estimate that the state currently has fewer than 2 days below freezing a year. [Note that this does not account for year-to-year variability; the 2009–2010 winter had many freezing days in Florida (National Weather Service 2010).] It is surprising that all regions contain at least one model run with an increase in frost days. These estimates come from the low-emissions scenario B1. Even in that scenario, most models project a decrease in the number of frost days. In general, the number of frost days seems likely to be reduced. The magnitude is uncertain, but it is reasonable to assume that there will be a reduction in the number of weeks of frost days in most regions, particularly in the North.

The models tend to project an increase in extreme precipitation, but not consistently. None of the projected changes in ***maximum 5-day precipitation*** are significant; however, the maximum precipitation is projected to rise in the Northwest, Midwest, Northeast and Southeast, although the change in the Northwest is virtually zero. The amounts are projected to decrease elsewhere. Here too, the range from maximum to minimum is very wide, suggesting that all regions could see substantial increases or decreases in 5-day maximum precipitation.

Finally, the ***number of days with more than 0.4 inch (10 millimeters) of precipitation*** is projected to increase in five of the eight regions in the contiguous 48 states; however, only two of the regions have changes well above one day. Generally, the northern regions are projected to see an increase and the southern regions a decrease or no change. As with the change in maximum 5-day precipitation, none of the changes are significant and the range across models is very wide, leaving the possibility that all regions could have increases or decreases.

4.3.4 Changes in Sea Level

Three components to *relative* sea-level rise at any given coastal location (i.e., how much sea-level rise is observed at a given location) are important for analysis. The first is average global (eustatic) sea level. The change in eustatic sea level resulting from changes in climate often receives the most attention.

The second component is the regional change in sea level. There are important regional differences in sea-level projections (indeed, current sea levels around the world are not uniform). Differences in ocean temperatures, salinity, and changes in ocean circulation result in different changes in sea level at a subcontinental scale; for example, the IPCC reports that sea-level rise in the Northeast may be about 3 inches (0.1 meter) higher than in the Southeast. These differences between regions of the world could be +0.5 foot (+0.1 meter), see Meehl et al. (2007) and Bamber et al. (2009).

The third component reflects whether coastal lands are rising or sinking (uplift or subsidence). The weight of glaciers covering much of the Northern Hemisphere tens of thousands of years ago lowered the land below them. As the glaciers retreated, the land began to rise (uplift), particularly in northern areas. Many other coastal areas are sinking (subsiding) because of the damming of rivers, high levels of sedimentation in deltas such as in the Mississippi River Delta, and the pumping of groundwater. Also, shifts in the Earth's tectonic plates (plate tectonics) can cause either uplift or subsidence in coastal areas.

The *observed* rates of sea-level rise are relatively high along the Gulf Coast and mid-Atlantic, lower along the east and west coasts, and negative in the far northwest. Clearly, there are different rates of subsidence and even uplift. Relative rates of sea-level rise below about 4 inches (0.1 meter) suggest there is uplift. That seems to be the case along most of the West Coast. With the exception of some areas in the Northeast, the East and Gulf Coasts are, in general, subsiding.

During the 20th century, global sea levels rose about 0.06 to 0.08 inch (1.5 to 2 millimeters) per year, but since the early 1990s have been rising at a rate of 0.12 inch (3 millimeters) per year. Given that rates of sea-level rise can fluctuate naturally, it is not clear whether the apparent acceleration of sea level is the result of anthropogenic or natural causes (Bindoff et al. 2007).

Projections of future sea-level rise vary widely. The IPCC projects that sea level will rise 8 inches to 2 feet (0.2 to 0.6 meter) by 2100 relative to 1990 (Solomon et al. 2007). This projection, however, only partially accounts for potentially significant melting of major ice sheets in Greenland and West Antarctica (Oppenheimer et al. 2007). These ice sheets contain enough water to raise sea levels 23 feet (7 meters) or more, but it would take centuries to millennia for that amount of sea-level rise to occur. The U.S. Global Change Research Program has concluded that sea-level rise will, however, likely exceed the IPCC projection (Climate Change Science Program 2008a).

Several studies published since the IPCC report (Solomon et al. 2007) estimate that sea levels could rise 5 to 6.5 feet (1.5 to 2 meters) by 2100 (Pfeffer et al. 2008; Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) conclude that the most likely increase in sea levels by 2100 is 2.6 feet (0.8 meter) relative to 1990. A recently released report by the National Research Council projects that mean sea level will rise 3 to 9 inches (8 to 23 centimeters) by 2030 relative to 2000, 7 to 19 inches (18 to 48 centimeters) by 2050, and 20 to 55 inches (50 to 140 centimeters) by 2100 (National Research Council 2012).

MAGICC (Wigley 2008) was used to estimate the eustatic sea-level rise for 2050 and 2100 relative to year 2010 for each emissions scenario. As with the climate projections, combinations of low, medium, and high GHG-emissions scenarios, climate sensitivity, and rates of melting of ice from glaciers and major ice sheets were used. Parameters for each scenario were set as follows:

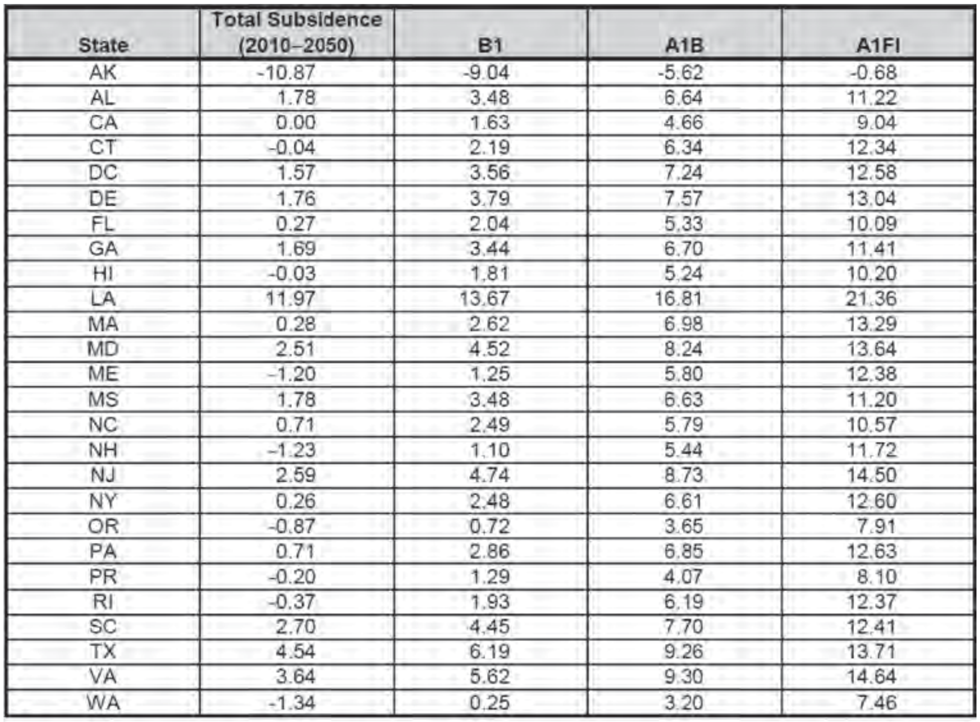
- B1—sensitivity of 1.5°C, low ice melt
- A1B—sensitivity of 3.0°C, medium ice melt
- A1FI—sensitivity of 4.5°C, high ice melt

Note that even the high ice-melt scenario does not completely account for a rapid melting of the Greenland or the West Antarctic Ice Sheet should either of those events occur. The average of six GCMs used by the IPCC for sea-level rise modeling that were common with those used by MAGICC were used in the analysis. The values in the models are expressed as scalars to the eustatic rate at 0.5° × 0.5° resolution using a GIS. An average rate of sea-level rise was then calculated by state and used the spatial average of cells falling within 62 miles (100 kilometers) of the state's shoreline to obtain the regional average scalar per state.

Estimates of relative local sea-level rise accounted for subsidence or uplift in the coastline by examining differences in observed sea-level rates along the U.S. coasts. Tide gauge data were obtained for all long-term gauges (minimum of 30 years) from the National Oceanic and Atmospheric Administration (NOAA 2008). For the two states without tide gauges—New Hampshire and Mississippi—the state averages from Maine and Alabama were used, respectively. As the tide gauge average includes a climate and non-climate component, the climate component was removed by using the current eustatic rate of 0.7 inch (1.8 millimeters) per year from the IPCC (Solomon et al. 2007), adjusted by the regional scalar. Annual subsidence rates were assumed to continue at historic rates from 2010 to 2100. The eustatic rates were then scaled by the state-specific regional scale values and added in the total subsidence (or uplift) to estimate relative sea-level rise by state.

State-by-state projections of sea-level rise by 2050 and 2100 relative to 2010 are presented in Tables II.3 and II.4 (note that for large states projections could very well vary along the coastal border, but these are not reflected in the tables). The B1, A1B, and A1FI columns estimate net sea-level rise by state for each of the SRES scenarios accounting for the combination of sea-level rise and subsidence (or uplift). Most states are projected to have 1 foot (0.3 meter) or less of relative sea-level rise by 2050. Louisiana is projected to have at least 1 foot (0.3 meter) and up to almost 2 feet (0.61 meter) by 2050. The increase in eustatic sea-level rise reduces the apparent decrease in relative sea level in Alaska from 9 inches (0.23 meter) to less than 1 inch (0.025 meter). Projected subsidence rates for the next 40 years for most states are a few inches or less; however,

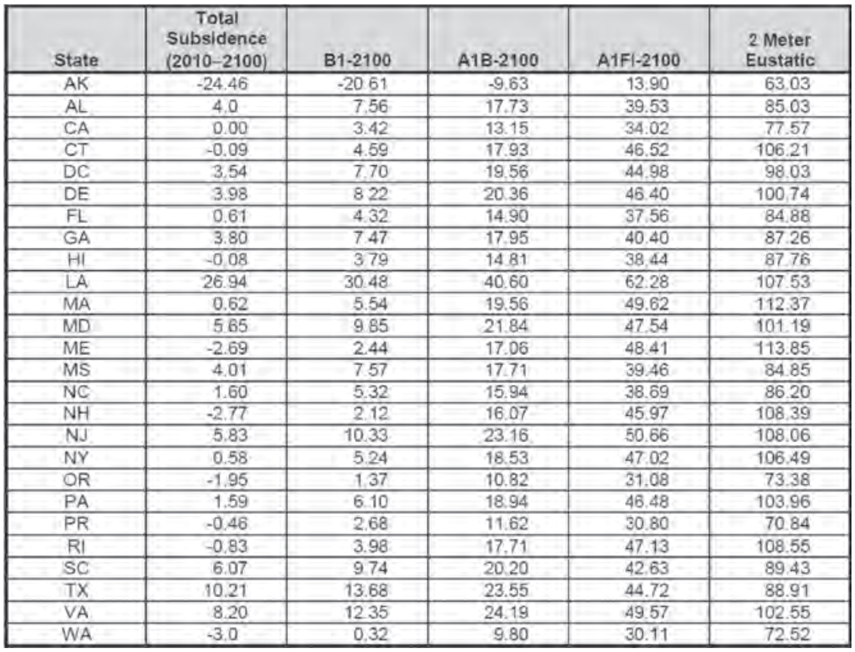
Table II.3. Total relative sea-level rise by 2050 (relative to 2010) in inches.



State	Total Subsidence (2010–2050)	B1	A1B	A1FI
AK	-10.87	-9.04	-5.62	-0.68
AL	1.78	3.48	6.64	11.22
CA	0.00	1.63	4.66	9.04
CT	-0.04	2.19	6.34	12.34
DC	1.57	3.56	7.24	12.58
DE	1.76	3.79	7.57	13.04
FL	0.27	2.04	5.33	10.09
GA	1.69	3.44	6.70	11.41
HI	-0.03	1.81	5.24	10.20
LA	11.97	13.67	16.81	21.36
MA	0.28	2.62	6.98	13.29
MD	2.51	4.52	8.24	13.64
ME	–1.20	1.25	5.80	12.38
MS	1.78	3.48	6.63	11.20
NC	0.71	2.49	5.79	10.57
NH	–1.23	1.10	5.44	11.72
NJ	2.59	4.74	8.73	14.50
NY	0.26	2.48	6.61	12.60
OR	-0.87	0.72	3.65	7.91
PA	0.71	2.86	6.85	12.63
PR	-0.20	1.29	4.07	8.10
RI	-0.37	1.93	6.19	12.37
SC	2.70	4.45	7.70	12.41
TX	4.54	6.19	9.26	13.71
VA	3.64	5.62	9.30	14.64
WA	-1.34	0.25	3.20	7.46

Note: Eustatic sea level rise by 2050 is 1.65 inches for B1, 4.72 inches for A1B, and 9.17 inches for A1FI.

Table II.4. Total relative sea-level rise by 2100 (relative to 2010) in inches.



State	Total Subsidence (2010–2100)	B1-2100	A1B-2100	A1FI-2100	2 Meter Eustatic
AK	-24.46	-20.61	-9.63	13.90	63.03
AL	4.0	7.56	17.73	39.53	85.03
CA	0.00	3.42	13.15	34.02	77.57
CT	-0.09	4.59	17.93	46.52	106.21
DC	3.54	7.70	19.56	44.98	98.03
DE	3.98	8.22	20.36	46.40	100.74
FL	0.61	4.32	14.90	37.56	84.88
GA	3.80	7.47	17.95	40.40	87.26
HI	-0.08	3.79	14.81	38.44	87.76
LA	26.94	30.48	40.60	62.28	107.53
MA	0.62	5.54	19.56	49.62	112.37
MD	5.65	9.85	21.84	47.54	101.19
ME	-2.69	2.44	17.06	48.41	113.85
MS	4.01	7.57	17.71	39.46	84.85
NC	1.60	5.32	15.94	38.69	86.20
NH	-2.77	2.12	16.07	45.97	108.39
NJ	5.83	10.33	23.16	50.66	108.06
NY	0.58	5.24	18.53	47.02	106.49
OR	-1.95	1.37	10.82	31.08	73.38
PA	1.59	6.10	18.94	46.48	103.96
PR	-0.46	2.68	11.62	30.80	70.84
RI	-0.83	3.98	17.71	47.13	108.55
SC	6.07	9.74	20.20	42.63	89.43
TX	10.21	13.68	23.55	44.72	88.91
VA	8.20	12.35	24.19	49.57	102.55
WA	-3.0	0.32	9.80	30.11	72.52

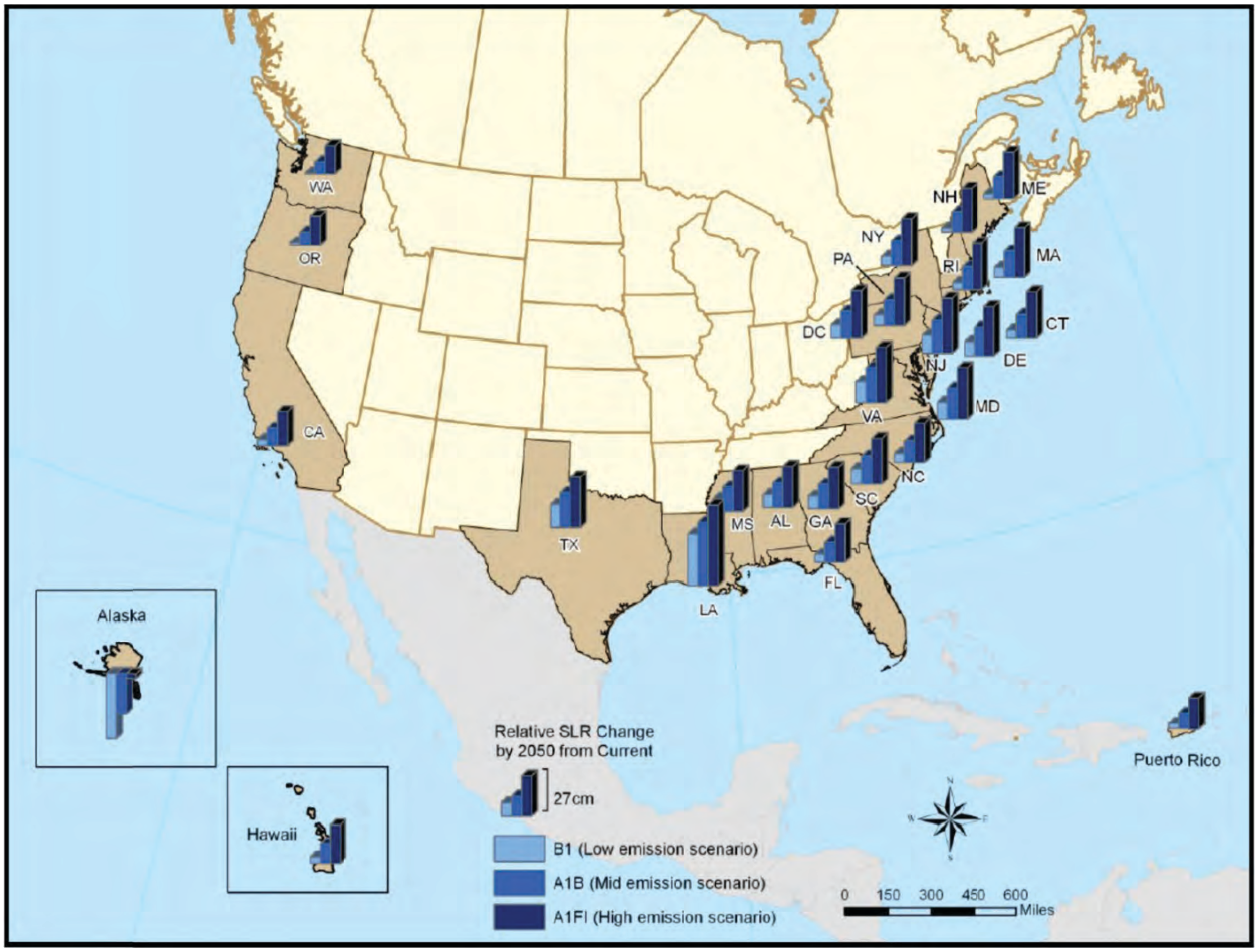


Figure II.12. Projected sea-level rise, 2050 relative to 2010.

Louisiana is projected to subside by about 1 foot (0.3 meter), whereas Alaska is projected to have uplift of almost 1 foot. The state projections are displayed in Figure II.12.

4.4 Summary

This chapter has provided the context within which adaptation assessment will occur. Not only does the transportation official need to be concerned about the direct impacts of climate stressors on the transportation system, but ultimately changes in population, land use, and transportation systems themselves will either exacerbate or provide solutions for the much broader impacts on society. The United States in 2050 (and certainly in 2100) will be a very different country than it is today. The population will be much larger, older, more diverse, and heavily urban. Perhaps most importantly for this research, much of this population growth will occur in areas of the country projected to see potentially significant changes in climate (for example, the Southwest and Florida). In addition, it is expected that the transportation system will be much "smarter," with the application of advanced sensors and communication technology that will provide opportunities for transportation system managers to respond to changes in climatic conditions in a more dynamic way. The need to rehabilitate much of the U.S. transportation system over the next 40 years also provides opportunities to incorporate a climate-sensitive perspective on facility design and system operations in areas especially vulnerable to changing conditions.

The next chapter discusses the types of impacts that might occur given different changes in climatic conditions. As indicated in this chapter, there is a great deal of uncertainty associated with what climate changes will occur in the future. However, given recent trends in weather conditions and based on the best science available for forecasting expected climate characteristics, it makes sense to consider how these future characteristics should affect the design of facilities that could last well into the latter half of this century, and how they in the shorter term might affect system operations and maintenance.

CHAPTER 5

Potential Impacts on the U.S. Road System

5.1 Introduction

The study of impacts of climate change on the U.S. transportation system has emerged as an important area of research in recent years (Committee for Study on Transportation Research Programs to Address Energy and Climate Change 2009). While many of these studies are overviews of the impacts to the entire transportation network, there is also a growing body of research that specifically addresses impacts on the highway system itself. Comprehensive reviews of regional, national, and international literature on this topic have been conducted by several groups that cover research published up to 2012. For this research project, these reviews were updated and supplemented with more recently published papers and reports. The findings from this review reveal similar types of impacts on the highway system that have been identified by various groups. As could be expected in a country the size of the United States, the potential impacts of climate changes on highways are geographically widespread and affect both infrastructure and operations.

Three important literature reviews were found in the following reports:

- *U.S. DOT Gulf Coast Study, Phases 1 and 2:* As part of a study of potential climate impacts on the Gulf Coast transportation system, this study identified the changing climate factors likely to impact transportation, synthesizing findings by mode, geography, climate zone, and timeframe (Climate Change Science Program 2008b, ICF International 2012, FHWA 2012c).
- TRB *Special Report 290:* This report focuses on the consequences of climate change for the infrastructure and operations of the entire U.S. transportation system. The report provides an overview of the scientific consensus and highlights flooding of coastal roads as a result of global rising sea levels, coupled with storm surges and land subsidence in some areas, as one of the most severe impacts on the road system in the United States (Committee on Climate Change and U.S. Transportation 2008).
- *Global Climate Change Impacts in the United States:* This report presents a summary of current scientific information on climate change and on the impacts of climate change on the United States divided by sector (including transportation) and by region of the country (Karl et al. 2009).

The literature consistently identifies four major categories of climate change factors and associated impacts to the highway system; these categories are discussed in the following section.

5.2 Climate Change Impacts on the Highway Network

As illustrated in Figure II.13, each of the climate factors or drivers (A) has direct implications for the condition of highway infrastructure as well as for the operations and maintenance of this infrastructure (B). As the significance of these implications is assessed, transportation managers may select from a range of adaptation strategies to respond to these impacts (C). These adaptation responses will, in turn, affect the condition and resilience of the highway infrastructure, as well as the operations and maintenance requirements of the infrastructure addressed by the adaptation actions. In addition, climate drivers will have impacts on the ecological conditions in which transportation infrastructure is built and maintained; effects on the planning, design, and construction phases of the highway system; and impacts on the effectiveness of ecological mitigation measures. Through an adaptive management approach, transportation agencies can evaluate the effectiveness of adaptation strategies on system performance, and then tailor future adaptation actions to further improve performance and enhance the resilience of the highway network. By taking pro-active measures, transportation

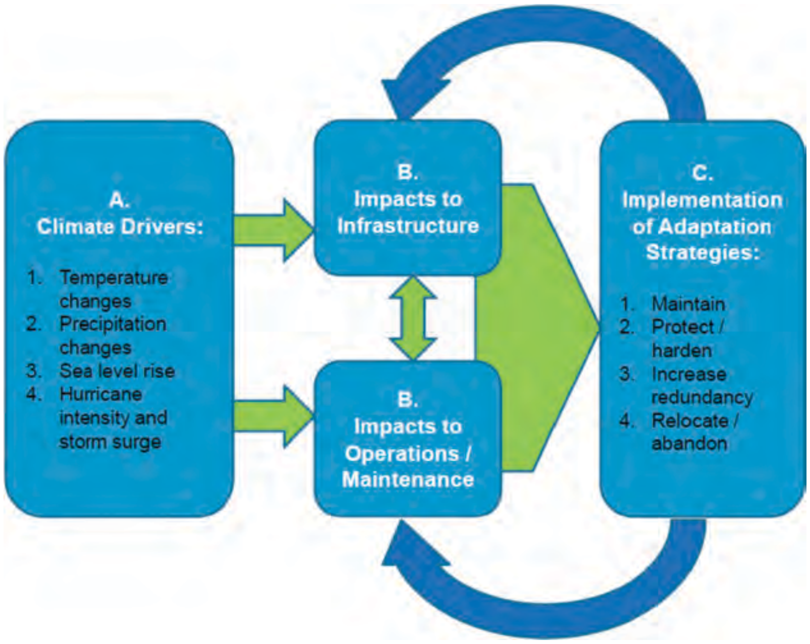


Figure II.13. Climate drivers that impact highway infrastructure and operations, resulting in need for adaptation strategies.

agencies can better protect their most vulnerable infrastructure and reduce the risk of system failure, with its impact on human life and economic activity.

This section reviews the range of climate impacts on infrastructure and operations/maintenance activities that may require the use of adaptation strategies. These are identified in Table II.5 and discussed in further detail in the following subsections.

Infrastructure will be affected most by those climate changes that cause environmental conditions to extend beyond the range for which the system was designed (Committee on Climate Change and U.S. Transportation 2008). As discussed in Section 3.3, the key climate factors and their major impacts are as follows:

1. *Temperature changes*, including changes in extreme maximum temperature that can damage road surfaces and affect crew operations, and changes in the range of maximum and minimum temperatures that can intensify damaging freeze–thaw cycles and melt permafrost;
2. *Precipitation changes*, including changes in overall precipitation levels which can lead to more rapid infrastructure deterioration, and increased intense precipitation events which can damage roads and disrupt operations;
3. *Sea-level rise* that can inundate coastal roads and increase areas flooded from coastal storms; and
4. *Increased intensity of hurricanes and higher storm surges*, which can cause infrastructure damage and failure and create evacuation challenges.

The following sections discuss the range of climate impacts on infrastructure and operations/maintenance activities.

5.2.1 Temperature Changes

Change in Extreme Maximum Temperature

The literature points to a likely increase in very hot days and heat waves. As discussed in Section 4.3, heat extremes and heat waves will continue to become more intense, longer lasting, and more frequent in most regions during the 21st century (Committee on Climate Change and U.S. Transportation 2008). Increasing periods of extreme heat will place additional stress on infrastructure, reducing service life and increasing maintenance needs.

Impacts on Highway Infrastructure. Extreme maximum temperature and prolonged duration of heat waves are expected to lead to premature deterioration of infrastructure. Temperature increases have the potential to affect and reduce the life of asphalt road pavements through softening and traffic-related rutting (Karl et al. 2009, CNRA 2009, Field et al. 2007, CSIRO et al. 2007, Maine DOT 2009). Extreme heat can also stress the steel in bridges through thermal expansion and movement of bridge joints and paved surfaces (Karl et al. 2009, CSIRO et al. 2007, New York City Panel on Climate Change 2010).

Impacts on Operations/Maintenance. The increase in very hot days and extended heat waves are expected to

Table II.5. Summary of climate change impacts on the highway system.

Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
Temperature		
Change in extreme maximum temperature	• Premature deterioration of infrastructure. • Damage to roads from buckling and rutting. • Bridges subject to extra stresses through thermal expansion and increased movement.	• Safety concerns for highway workers limiting construction activities. • Thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs. • Vehicle overheating and increased risk of tire blowouts. • Rising transportation costs (increase need for refrigeration). • Materials and load restrictions can limit transportation operations. • Closure of roads because of increased wildfires.
Change in range of maximum and minimum temperature	• Shorter snow and ice season. • Reduced frost heave and road damage. • Later freeze and earlier thaw of structures because of shorter freeze-season lengths. • Increased freeze–thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces. • Increased slope instability, landslides, and shoreline erosion from permafrost thawing leads to damaging roads and bridges due to foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost). • Hotter summers in Alaska lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.	• Decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, and result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles. • Longer road construction season in colder locations. • Vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons). • Roadways built on permafrost likely to be damaged due to lateral spreading and settlement of road embankments. • Shorter season for ice roads.
Precipitation		
Greater changes in precipitation levels	• If more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction. • Increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration). • Less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode. • Road embankments could be at risk of subsidence/heave. • Subsurface soils may shrink because of drought.	• Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents). • Roadways and underground tunnels could close due to flooding and mudslides in areas deforested by wildfires. • Increased wildfires during droughts could threaten roads directly or cause road closures due to fire threat or reduced visibility. • Clay subsurfaces for pavement could expand or contract in prolonged precipitation or drought, causing pavement heave or cracking.

(continued on next page)

Table II.5. (Continued).

Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/Maintenance
Increased intense precipitation, other change in storm intensity (except hurricanes)	• Heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting), which could lead to permanent road closures. • Heavy precipitation and increased runoff can cause damage to tunnels, culverts, roads in or near flood zones, and coastal highways. • Bridges are more prone to extreme wind events and scouring from higher stream runoff. • Bridges, signs, overhead cables, and tall structures could be at risk from increased wind speeds.	• The number of road closures due to flooding and washouts will likely rise. • Erosion will occur at road construction project sites as heavy rain events take place more frequently. • Road construction activities could be disrupted. • Increases in weather-related highway accidents, delays, and traffic disruptions are likely. • Increases in landslides, closures or major disruptions of roads, emergency evacuations, and travel delays are likely. • Increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/maneuverability, lane obstruction (debris), and treatment chemical dispersion. • Lightning/electrical disturbance could disrupt transportation electronic infrastructure and signaling, pose risk to personnel, and delay maintenance activity.
Sea Level		
Sea-level rise	• Erosion of coastal road base and undermining of bridge supports due to higher sea levels and storm surges. • Temporary and permanent flooding of roads and tunnels due to rising sea levels. • Encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events). • Further coastal erosion due to the loss of coastal wetlands and barrier islands removing natural protection from wave action.	• Coastal road flooding and damage resulting from sea-level rise and storm surge. • Increased exposure to storm surges. • More frequent and severe flooding of underground tunnels and other low-lying infrastructure.
Hurricanes		
Increased hurricane intensity	• Increased infrastructure damage and failure (highway and bridge decks being displaced).	• More frequent flooding of coastal roads. • More transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods). • More coastal evacuations.

affect highway operations and maintenance in several ways. The first is the probable limit on construction activities and the number of hours road crews can work due to health and safety concerns for highway workers (Karl et al. 2009; Peterson et al. 2008). The increase in extreme heat could also lead to load restrictions on roads. Pavement damage and buckling will disrupt vehicle movements (Karl et al. 2009). Extreme heat could disrupt vehicle operations because of overheating and increased risk of tire blowouts in heavily loaded vehicles (Karl et al. 2009; Peterson et al. 2008). Higher temperatures could lead to an increased need for refrigerated freight movement, and thus result indirectly in higher transportation costs (Karl et al. 2009; CNRA 2009).

A secondary impact of extreme and extended periods of heat, when combined with reduced precipitation, is the projected increased risk of wildfires, especially in the Southwest. Fire poses a risk to infrastructure and travelers and can necessitate road closures (Karl et al. 2009).

Change in Range of Maximum and Minimum Temperatures

Changes in the projected range of temperatures, including seasonal changes in average temperatures, can also affect highway systems. The increase in range of temperatures will likely benefit highways in some ways, while increasing risks in others.

Impacts on Highway Infrastructure. Warmer winters will likely lead to less snow and ice on roadways, and incidence of frost heave and road damage caused by snow and ice in southern locations is likely to decline. However, in some regions, warmer winters could also increase the freeze–thaw conditions that create frost heaves and potholes on road and bridge surfaces, particularly in northern locations that previously experienced below-freezing temperatures throughout much of the winter. They may lead to an increase in freeze–thaw conditions in northern states, creating frost heaves and potholes on road and bridge surfaces that increase maintenance costs. Repairing such damage is already estimated to cost hundreds of millions of dollars annually in the United States (Peterson et al. 2008).

In Alaska, warmer temperatures will likely adversely affect infrastructure for surface transportation. Permafrost thaw in Alaska will damage road infrastructure due to foundation settlement and is the most widespread impact (Larsen 2008). Permafrost thaw will also reduce surface load-bearing capacity and potentially trigger landslides that could block highways. Roadways built on permafrost already have been damaged as the permafrost has begun to melt and ground settlement has occurred leading to costly repairs for damaged roads. Dealing with thaw settlement problems already claims a major portion of highway maintenance dollars in Alaska (Karl et al. 2009). A study in Manitoba, Canada, projects the degradation of permafrost beneath road embankments will accelerate because of warmer air temperatures. The symptoms of permafrost degradation on road embankments are lateral spreading and settlement of road embankments. This can create sharp dips in road surfaces which require extensive patching every year and lead to dangerous conditions for motorists (Alfaro 2009).

In southern Canada, studies suggest that rutting and cracking of pavement will be exacerbated by climate change and that maintenance, rehabilitation, or reconstruction of roadways will be required earlier in the design life (Mills et al. 2007). Similarly, simulations for pavement in Alberta and Ontario show that temperature increases will have a negative impact on the pavement performance in the Canadian environment. As temperature increases, accelerated pavement deterioration due to traffic loads on a warmer pavement was expected and observed. An increase in temperature would facilitate rutting because the pavement is softer. Pavement movement due to loads on a softer pavement would also result in increased cracking. Overall temperature changes significantly affected the level of pavement distress for the international roughness index, longitudinal cracking, alligator cracking, asphalt concrete deformation, and total deformation (Smith et al. 2008).

The effects of changing temperatures are particularly apparent in the Arctic. Warming winter temperatures, especially in the high northern latitudes of Alaska, could cause the upper layer of permafrost to thaw. Over much of Alaska, the land is generally more accessible in winter, when the ground is frozen and ice roads and bridges formed by frozen rivers are available (Committee on Climate Change and U.S. Transportation 2008, Karl et al. 2009). Winter warming would therefore shorten the ice road season and affect access and mobility to northern regions. Thawing permafrost could also damage highways as a result of road base instability, increased slope instability, landslides, and shoreline erosion. Permafrost melt could damage roads and bridges directly through foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost) or indirectly through landslides and rockfalls. In addition, hotter summers in Alaska and other mountainous western locations may lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.

Impacts on Operations/Maintenance. The change in range of maximum and minimum temperatures will likely produce both positive and negative impacts on highway operations/maintenance. In many northern states, warmer winters 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 (Karl et al. 2009).

On the other hand, warmer winter temperatures could also have negative impacts on highway operations and maintenance. Greater vehicle load restrictions may be required to minimize damage to roadways when they begin to subside and lose bearing capacity during the spring thaw period. With the expected earlier onset of seasonal warming, the period of springtime load restrictions might be reduced in some areas, but it is likely to expand in others with shorter winters but longer thaw seasons (Peterson et al. 2008).

In the far north, the season for ice roads will likely be compressed. Temporary ice roads and bridges are commonly used in many parts of Alaska for access to northern communities. Rising temperatures have already shortened the season during which these critical facilities can be used (Karl et al. 2009; Peterson et al. 2008; Field et al. 2007).

The indirect effects of changing temperatures on travel behavior are also a consideration. For example, tourism-related traffic is projected to increase in Maine because of the longer summer season and as more people seek to escape increasingly hot summers in other parts of the country (Maine DOT 2009). Conversely, southern destinations (e.g., Florida, the desert Southwest) could see decreased summertime tourism.

5.2.2 Precipitation Changes

Changes in Overall Precipitation

As discussed in further detail in Section 4.3, changes in precipitation—of both rain and snow—will vary widely across the various regions in the United States. These changes are expected to affect highways in several ways, depending on the specific regional precipitation levels and geographic conditions.

Impacts on Highway Infrastructure. In areas with increased precipitation, there is greater risk of flooding. In other areas, more precipitation may fall as rain rather than snow in winter and spring, increasing the risk of landslides, slope failures, and floods from the runoff, which can cause road washouts and closures. In addition, northern areas are projected to have wetter winters, exacerbating spring river flooding. In other areas, the increase in precipitation could lead to higher soil moisture levels affecting the structural integrity of roads, bridges, and tunnels and lead to accelerated deterioration.

If soil moisture levels become too high, the structural integrity of roads, bridges, and tunnels, which in some cases are already under age-related stress and in need of repair, could be compromised. Standing water can also have adverse impacts on road base (Karl et al. 2009; Smith et al. 2008). Overall, the increased risk of landslides, slope failures, and floods from runoff will lead to greater road repair and reconstruction needs (Karl et al. 2009).

Some regions of the country will experience decreased precipitation. Where there is less precipitation, there may not be enough runoff to dilute surface salt causing steel reinforcing in concrete structures to corrode. In some regions, drought is expected to be an increasing problem.

Impacts on Operations/Maintenance. Changes in rain, snowfall, and seasonal flooding can affect safety and maintenance operations on roads. More precipitation increases weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents) (Koetse and Rietvelda 2009). In New York City and other urban areas, precipitation-related impacts may include increased street flooding and associated delays, and an increase in risk of low-elevation transportation flooding and water damage (New York City Panel on Climate Change 2010). Increases in road washouts and landslides and mudslides that damage roads are expected.

Climate models tend to show wetter winters but drier summers. Dry summers or droughts can lead to increased wildfires, which could threaten roads and other transportation infrastructure directly or cause road closures due to reduced visibility. Areas with both wetter winters and drier summers may be particularly at risk, as wetter winters may promote increased springtime vegetation growth, in turn providing more fuel for summer wildfires. There is also increased susceptibility to mudslides in areas deforested by wildfires, particularly if wintertime precipitation increases (Karl et al. 2009).

Increased Intense Precipitation

Heavier rainfall downpours and more intense storms are very likely to continue to become more frequent in widespread areas of the United States (Committee on Climate Change and U.S. Transportation 2008). This intense precipitation has immediate effects on highways and could cause changes to the ecological system that ultimately affect highway infrastructure and operations/maintenance.

Impacts on Highway Infrastructure. The increase in intense precipitation could have major impacts on infrastructure. In areas with heavy winter rain, mudslides and rockslides can damage roads from washouts and undercutting and lead to permanent road closures. For example, winter rain has caused yearly washouts of Highway 1 in California (Peterson et al. 2008). Heavy precipitation and increased runoff during winter months are likely to increase the flood damage to tunnels, culverts, and coastal highways (CNRA 2009). The combination of a generally drier climate in the Southwest in the future, which will increase the chance of drought and wildfires, with more frequent extreme downpours (and occasionally wet winters) is likely to cause more mudslides and landslides that can disrupt major roadways (CNRA 2009). In California, the debris impacts generated by intense precipitation are well known. As these events become more intense, the state will incur even greater costs for more frequent repair (CNRA 2009). An Australian study found that in Victoria the projected increase in the frequency and intensity of extreme rainfall events has the potential to cause major flood damage to roads—especially tunnel infrastructure—due to acceleration in the degradation of materials, structures, and foundations of transport infrastructure from increased ground movement, changes in groundwater affecting the chemical structure of foundations and fatigue of structures from extreme storm events (CSIRO 2007). Bridges are more prone to extreme wind events and scouring from higher stream runoff, and bridges, signs, overhead cables, and tall structures face increased risk from greater wind speeds.

Impacts on Operations/Maintenance. Generally, intense precipitation and increased runoff during winter months are likely to increase the flood damage to tunnels, culverts, and coastal highways. The number of road closures due to flooding and washouts will likely increase as will the potential for extreme incidents of erosion at project sites as more rain falls in heavy rain events (Maine DOT 2009).

The increase in heavy precipitation will inevitably cause increases in weather-related accidents, delays, and traffic disruptions in a network already challenged by increasing congestion. There will be potential flooding of evacuation routes and construction activities will be more frequently disrupted (Karl et al. 2009).

5.2.3 Sea-Level Rise

Sea levels will continue to rise in the 21st century as a result of thermal expansion and the possible loss of mass from ice sheets (Committee on Climate Change and U.S. Transportation 2008), as discussed in Section 3.3. Infrastructure in coastal areas is expected to be heavily affected by rising sea levels, often compounded by regional subsidence (the sinking of a land mass due to compaction of sediments or tectonic forces). Coastal highways are at risk from the combination of rising sea levels along with increased heightened coastal flooding potential from tropical and non-tropical storms (Oregon Coastal Management Program 2009). Storm surge risks related to hurricanes will be discussed in more detail in the next section.

Impacts on Highway Infrastructure. In many coastal states, the greatest impacts and largest projected damages to highway infrastructure will come from sea-level rise (CNRA 2009). Sea-level rise will also increase the risk of coastal flooding and damage to transportation infrastructure; the same storm surge will now have more elevation because of higher sea levels. Sea-level rise is likely to contribute to more frequent storm-related flooding of roads in coastal floodplains. An estimated 60,000 miles of coastal highway are already exposed to periodic flooding from coastal storms and high waves (Karl et al. 2009). Along with the temporary and permanent flooding of roads and tunnels, rising sea levels and storm surges will likely cause erosion of coastal road bases and bridge supports.

In addition to more frequent and severe flooding, underground tunnels and other low-lying infrastructure may also experience encroachment of saltwater, which can lead to accelerated degradation of infrastructure. This can reduce the structure's life expectancy, increase maintenance costs as well as the potential for structural failure during extreme events (Peterson et al. 2008, CSIRO 2007, New York City Panel on Climate Change 2010). Underground tunnels and other low-lying infrastructure will experience more frequent and severe flooding. Higher sea levels and storm surges will also erode road base and undermine bridge supports. The loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action (Karl et al. 2009).

Impacts on Operations/Maintenance. Studies from a number of coastal states indicate thousands of miles of major roadway are at risk of flooding and erosion as climate change and land subsidence combine to produce a relative sea-level rise (Climate Change Science Program 2008b; Maine DOT 2009; Heberger et al. 2009). As coastal roads are flooded more frequently and for longer periods of time, road closures may become longer and the cost of repair may rise. These affected roads may need to be protected by raising or re-routing the road (Heberger et al. 2009). The significance of the vulnerability of coastal roads is compounded because many coastal highways serve as evacuation routes during hurricanes and other coastal storms. These routes could become seriously compromised and lead to evacuation route delays and stranded motorists (Karl et al. 2009).

5.2.4 Increased Hurricane Intensity

Hurricanes are projected to increase in intensity, with larger peak wind speeds and more intense precipitation (Committee on Climate Change and U.S. Transportation 2008, Peterson et al. 2008). The number of Category 4 and 5 hurricanes is projected to increase, while the number of less powerful hurricanes is projected to decrease (Bender et al. 2010; Knutson

2013). Three aspects of hurricanes are relevant to transportation: precipitation, winds, and wind-induced storm surge. Stronger hurricanes have longer periods of intense precipitation, higher wind speeds (damage increases exponentially with wind speed), and higher storm surge and waves. Increased intensity of strong hurricanes could lead to more evacuations, infrastructure damage and failure, and transportation interruptions in transportation service (Karl et al. 2009). The prospect of an increasing number of higher category hurricanes has serious implications for the highway system.

Impacts on Highway Infrastructure. Road infrastructure for passenger and freight services is likely to face increased flooding by strong hurricanes (Karl et al. 2009). Prolonged inundation can lead to long-term weakening of roadways. A study of pavements submerged longer than 3 days during Hurricane Katrina (some were submerged several weeks) found that asphalt concrete pavements and subgrades suffered a permanent strength loss equivalent to 2 inches of pavement (Gaspard et al. 2007).

With an increase in future hurricane intensity, there will also be more damage to roadway infrastructure. Roads and bridges can be damaged during hurricanes by wave battering (from water driven inland by storm surge) and high winds. Concrete bridge decks weighing many tons can literally be blown off during hurricanes, as seen during Hurricanes Katrina and Rita. The widespread damage to highways from these hurricanes illustrated the powerful effects of these intense tropical storms. Damage to signs, lighting fixtures, and supports also is a product of hurricanes force winds.

Impacts on Operations/Maintenance. More intense storms will leave behind greater volumes of debris on roads, which causes road closures and disruptions until it can be cleared (Karl et al. 2009). Damage to the highway networks caused by the storms increases the challenge for system operations and emergency management. In addition, there will be more frequent and potentially more extensive emergency evacuations, placing further strain on highways. At the same time, sea-level rise may render existing evacuation routes less useable in future storms.

5.3 Climate Impact to Ecological Conditions

In addition to the direct effects of climate changes on highways, climate change will affect ecological dynamics in ways that will have implications for transportation systems. Highway infrastructure interacts with ecosystems in a number of different ways. Highway construction can destroy ecosystems by displacing natural environments, such as wetlands. Roads can act as a barrier, restricting the movement of flora and fauna and fragmenting ecosystems and changing the natural flow of water across their right-of-way. Vehicles can also be a hazard to wildlife, killing or injuring animals as they attempt to cross roads to escape rising waters or wildfires. Roads can also be a local source of pollution and damage water bodies, as with the materials that run off roads with rainfall, and in addition affect the level of soil saturation. Transportation professionals have worked for years with resource agencies and ecologists to understand these interactions and develop strategies to reduce or mitigate the negative effects of highways on ecosystems—and to identify opportunities to restore and strengthen compromised environments.

Specifically with respect to climate change, changing temperatures, precipitation levels and extreme weather events can significantly alter the ecosystem in highly vulnerable areas. For example, the National Climate Assessment draft report (as of 2013) noted in its chapter on ecosystems that "coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts" (NCADAC 2013).

The Practitioner's Guide (Part I of this volume) discusses the impacts to ecological conditions in more detail.

5.4 Adaptation Strategies

5.4.1 Domestic Strategies

Numerous adaptation strategies have been identified as a result of climate change studies. As with adaptation planning in general, at this stage, most plans identify adaptation strategies at a high level—a planning level, rather than an implementation level. For instance, agencies might identify the need to update design standards for the new climate future but not specify which standards or what the new standards should be.

Vermont

In the aftermath of Tropical Storm Irene, the Vermont Agency of Transportation (VTrans) put together an climate change adaptation policy/strategy based on its experience with the storm and its aftermath. As noted in the policy, its primary goal is to "minimize long-term societal and economic costs stemming from climate change impacts on transportation infrastructure" (VTrans 2012a). The policy relates to several of the VTrans's goals:

> "*Excellence & Innovation:* Cultivate and continually pursue excellence and innovation in planning, project development, and customer service:
>
> - Ensure that there are viable alternative routes around vulnerable infrastructure such as bridges and roadways.

> "*Safety:* Make safety a critical component in the development, implementation, operation and maintenance of the transportation system:
>
> - Develop contingency plans for a wide variety of climate impacts to be implemented as data/information becomes available;
> - Utilize information technology to inform stakeholders during times of emergency;
> - Educate the public and other stakeholders on the threats posed by climate change and fluvial erosion hazards;
> - Increase inspection of infrastructure if warranted by climate change indicators;
>
> "*Planning:* Optimize the movement of people and goods through corridor management, environmental stewardship, balanced modal alternatives, and sustainable financing:
>
> - Apply a decision-making framework to incorporate cost–benefit analyses into adaptive plans and policy;
> - Increase adaptive capacity among stakeholders so that adaptive planning can be quickly implemented upon realization of risk;
>
> "*Environmental Stewardship:* Build, operate, and manage transportation assets in an environmentally responsible manner:
>
> - Work to protect essential ecosystem functions that mitigate the risks associated with climate change;
> - Educate individuals within the agency to use best practices during recovery periods to avoid ecological damage that may further exacerbate risk;
> - Recognize the interconnected nature of our built environment with ecological processes.
>
> "*Preservation:* Protect the state's investment in its transportation system.
>
> - Policies must overcome short-term budgetary, social, and institutional constraints to avoid potentially untenable future costs" (VTrans 2012a).

Some specific initiatives undertaken by VTrans included the following (VTrans 2012a):

- **LiDAR (light detection and ranging) mapping:** VTrans, regional planning commissions, and some municipalities are undertaking LiDAR mapping efforts along primary transportation and river corridors to increase the precision of computerized flood models, update FEMA's 100-year floodplain maps, and support the use of risk assessment tools.
- **State asset management:** The state is collecting condition and performance data on state-owned small and large culverts, bridges, and pavement. VTrans is working towards development of more sophisticated deterioration models that will allow the agency to more effectively plan for long-term funding needs and to quantify performance trade-offs under different scenarios. It is expected that climate changes will require frequent updates of environmental factors in these models.
- **Flood resiliency training programs:** Flood resiliency training programs have been instituted to educate key audiences on best management practices, river dynamics and geomorphology, and potential impacts of floods on infrastructure. Participants include VTrans personnel such as heavy equipment operators, field supervisors, and design engineers; Tri-State (Maine, Vermont, and New Hampshire) partners; contractors; and consultants. These programs will increase the adaptive capacity of VTrans and allow for responsible reactions to natural disaster events in the future.
- **Transportation resiliency plan:** VTrans is developing methods and tools to identify roads, bridges, and other transportation infrastructure that are vulnerable to flooding and fluvial erosion; quantify risk as a means to prioritize needs; and evaluate strategies to mitigate risk. The purpose is to proactively identify transportation facilities that have a high risk of failing due to flooding so mitigation strategies can be implemented using available project development and funding mechanisms prior to the next disaster. These transportation resiliency plans will be developed on a watershed basis and will involve the integration of river corridor and transportation corridor planning.
- **Rapid culvert sizing:** VTrans has developed a computerized process to rapidly assess culvert specifications using a variety of site-specific and hydrological data sources. This tool allows VTrans to expedite support during emergencies and to reassess the vulnerability of culverts as precipitation models with higher certainty become available.
- **Resilient Vermont Project: Stronger Communities, Ecosystems, and Economies:** VTrans and a wide variety of stakeholders are compiling an inventory or map of resilience-building activities already underway, creating a shared definition of "resilience" specific to Vermont and allowing for prioritization of a variety of actions and investments to increase resilience.

As seen in this example from Vermont, adaptation strategies can be applied in several categories. The following subsections discuss adaptation strategies in other states.

Planning

Numerous adaptation plans recognize the general need to incorporate the changing climate into long-range planning. Florida's Climate Action Plan, for instance, recommends that the Florida DOT should update the Florida Transportation Plan to develop long-range goals, objectives, and strategies for adapting to potential impacts from climate change. Likewise, California proposes to incorporate climate change vulnerability assessment planning tools, policies, and strategies into existing transportation and investment decisions (e.g., regional planning, programming, and project planning) (Caltrans 2012). Similarly, Oregon's *Framework for Addressing Rapid Climate Change* recommended that state agencies integrate climate change preparation into existing sustainability plans, agency risk management plans, or other long-range plans.

Maryland also recommends integration of adaptation strategies into local comprehensive plans and implementing codes and ordinances, as well as integration of adaptation strategies into state plans and underlying management and regulatory programs. Some provide more specific recommendations on what these long-range planning considerations might be. The City of Punta Gorda, Florida, recommends constraining locations for certain high-risk infrastructure. The Houston–Galveston Area Council (H-GAC) recommends considering the appropriateness of different modes of transportation given climate change impacts and the increased costs to maintain and operate each mode, and suggests considering a longer-term view of infrastructure needs over the next 50 to 100 years (in terms of maintenance, construction, and rehabilitation costs). H-GAC also recommended using alternative paving products for higher temperatures. King County, Washington, has incorporated adaptive design strategies into planning documents such as the Transportation Needs Report and Six-Year Capital Improvement Plan.

As noted earlier, the French Broad River MPO in North Carolina has undertaken one of the most extensive efforts to integrate climate change adaptation into the regional transportation planning process. The types of strategies identified in the climate change chapter of the long-range transportation plan include the following (French Broad River MPO 2010):

1. Implement strategies to reduce risk of flooding (and other risks), including reviewing roads and bridges in flood-prone areas to ensure they are designed to handle the risk. Consider redesign to make existing structures more flood resilient. Design and construct roads and roadbeds to be resilient to flood impacts, especially based on the new floodplain maps that have been released by the state. Consider other potential hazards such as landslides and dam failures and their potential impact on transportation corridors.
2. Redesign railroads to make them more resilient to climate change impacts.
3. Develop the ability to deal with greater climate variability and associated temperature extremes. Factor in budgetary impacts caused by preparation for responding to temperature extremes.
4. Coordinate with the region's local governments and planning partners to link transportation with land use.
5. Use future scenarios in transportation and land use planning to design systems that are robust and resilient compared to just being optimized for current conditions and economics. Transportation systems that are designed to operate well under a range of future scenarios are superior to a single system design tied to one view of the future.
6. Pinch points on maps to show vulnerable "hotspots" that lack options. More drought, fires, and intense rainfall amounts will produce more landslides that can be a major disruption to main transportation corridors.
7. The region's local governments, emergency responders, and planning partners should work together to minimize the region's reliance on gasoline distribution sites out of the region, which makes the region more vulnerable to disruption.

Environmental Analysis

Several states and the federal government have taken steps to incorporate adaptation considerations into environmental analysis, specifically efforts relating to NEPA documentation. In 2011, for example, U.S. DOT agencies were given policy direction by the Secretary to consider climate change impacts in their activities (U.S. DOT 2011). California is operating under a governor's executive order that directs state agencies that are planning to construct projects in areas vulnerable to sea-level rise to consider a range of sea-level rise scenarios for the years 2050 and 2100 (California Executive Order S-13-08). State agencies are "urged to consider timeframe, risk-tolerance, and adaptive capacity when determining whether to adapt the project for potential sea-level rise impacts" (U.S. DOT 2011).

Design Standards

A number of plans list changes to design standards as a needed strategy to adapt to climate change—but at this stage few provide specifics. California, for instance, recommends developing transportation design and engineering standards to minimize climate change risks to vulnerable transportation infrastructure. Both H-GAC and the City of Punta Gorda recommended using paver blocks (which act as a form of permeable pavement) for parking lots to address stormwater runoff and the urban heat island effect (which will be exacerbated by global warming). Among those that do get to a greater level of detail, Maine DOT recommends upgrading design standards for water flow from Q50 to Q100 to build in resiliency in the face of extreme weather events. Again, King County is in the forefront here and is already incorporating climate change considerations into the project designs of bridges and culverts that are being rebuilt.

Infrastructure Retrofit

Some plans show an awareness of the need to integrate planning policy into the decision to retrofit, rather than approaching the issue from a purely engineering perspective. For instance, the Maryland plan identifies several engineering strategies for retrofitting coastal infrastructure to protect against sea-level rise, such as structural bulkheads, seawalls, or revetments. However, it also notes that larger decisions on whether to protect, relocate, or abandon infrastructure need to be made as well. In another example that addresses flooding risks, Washington State DOT's strategies focus on restoring natural processes. This includes limiting shoreline armoring, restoring shorelines, and targeted removal of dikes.

The Alaska Department of Transportation and Public Facilities has dedicated $10 million in funding to combat permafrost thawing under highways and is also actively working on drainage improvements and evacuation routes and shelters (Arroyo 2010, Coffey 2010).

Maintenance

Fewer strategies have been developed for maintenance procedures, although some of the design changes suggested are meant to reduce future maintenance costs. The Maine DOT has conducted a pipe and culvert vulnerability assessment, and the Maine DOT Bridge Maintenance Division completed a scour report. Based on this information, the Maine DOT is preparing bridge-specific scour plans. The Rogue River Basin, Oregon, plan recommends expanding road upgrading and maintenance such as the installation of larger culverts and regular culvert clean outs to prevent washouts during major storms and floods.

Operations

Although it is likely that transportation operations will change to respond to climate change—road weather programs, to name an obvious example—very few plans address operations at this point (Radow and Neudorff 2011). Responding to extreme weather events in an effective manner requires not only advanced coordination of the many agencies involved, but also rapid clearing of transportation lifelines, such as roads that lead into devastated areas. As was seen in Vermont's response to Tropical Storm Irene, the response to isolated communities and individual travelers required the coordinated effort of many different groups, with the state DOT playing a key coordinating and information clearinghouse role. California recommends incorporating climate change impact considerations into disaster preparedness planning for all transportation modes. The City of Punta Gorda, Florida, provides a similar recommendation. In a different approach to the issue, the Rogue River Basin, Oregon, plan suggests linking public transportation systems as much as possible to facilitate movement of people and equipment in emergency situations.

Public Outreach/Communications

A major challenge with respect to shorter-term extreme weather events and longer-term climate changes is conveying to the public the actions that can be taken to respond to particular events. This might entail improving road weather information systems (such as being done in Michigan) to providing information on the types of impacts climate change could have to the transportation system (such as being done in California, Maryland, and Washington).

Process Recommendations

Overall, it appears that most strategies identified have not yet been taken to the engineering level. This is consistent with the general state of practice of adaptation planning in the United States; given that most agencies have only started adaptation planning in the last few years, it will take some time to bring these strategies to the implementation level. It is also likely that as this happens, maintenance and operations will receive more study.

As a result, some adaptation strategies included in state and local plans are really process recommendations to further adaptation planning. For example, Florida identifies research as an immediate adaptation action. Alaska recommends creating a coordinated and accessible state-wide system for key data collection, analysis, and monitoring. Some governments have also identified the need for training and establishing criteria so agencies can better integrate climate change impacts into their planning efforts. King County, Washington, is a good example of this. The Climate Plan identified the need for training and educating the Road Services Division staff on expected changes in climate, how these changes potentially affect the facilities they manage, and how to identify adaptation solutions to address near- and long-term impacts.

Finally, some plans show an additional focus on the need for monitoring to assess how the climate is actually changing and whether adopted adaptation strategies will therefore need to be modified. For instance, New York City's risk-based approach to adaptation, Flexible Adaptation Pathways, is an iterative process that recognizes the multiple dimensions of climate hazards, impacts, adaptations, economic development, and other social factors. This iterative process is predicated on the establishment of climate change monitoring programs that can provide feedback to the process to allow for changing "pathways."

The adaptation strategies studied by King County's Road Services Division provides an illustrative example of the range of adaptation strategies an individual transportation agency might consider:

- Replacing or rehabilitating bridges in order to improve floodwaters conveyance and to avoid scour during high flows
- Using pervious pavement and other low-impact development methodologies to manage stormwater through reduced runoff and on-site flow control
- Modifying existing seawalls to avoid failures in transportation facilities
- Evaluating roadways to minimize their vulnerability to potential risk from landslides, erosion, or other failure triggers
- Developing new strategies to effectively respond to increasingly intense storms, including providing alternative transportation access
- Managing construction and operations to minimize effects of seasonal weather extremes
- Identifying opportunities to incorporate habitat improvements that buffer the effects of climate change on ecosystem health into project designs.

5.4.2 International Adaptation Strategies

Of the international reports reviewed, only three provided strategies for dealing with climate change impacts to roadway networks. And in most cases, the strategies were general calls for additional research in design and maintenance practices.

Canada

As *The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada* put it, "The key adaptation issues will surround not how to deal with potential impacts, but rather when to modify current design and maintenance practices," and the report recommends that study results should be discussed in the engineering community to move from exploratory research to practical guidance (Mills et al. 2007, p. 65).

The Canadian Council of Professional Engineers' report, *Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure*, which looked at the impacts of climate change on four types of infrastructure, classified its conclusions into seven themes and five recommendations—none of which call for far-reaching design approaches or solutions (PIEVC 2008):

- ***Themes***
  - Some infrastructure components have high engineering vulnerability to climate change.
  - Improved tools are required to guide professional judgment.
  - Infrastructure data gaps are an engineering vulnerability.
  - Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure.
  - Improvements are needed in design approaches.
  - Climate change is one factor that diminishes resiliency.
  - Engineering vulnerability assessment requires multidisciplinary teams.
- ***Recommendations***
  - Revise and update the Engineering Vulnerability Assessment Protocol.
  - Conduct additional work to further characterize the vulnerability of Canadian public infrastructure to climate change.
  - Develop an electronic database of infrastructure vulnerability assessment results.
  - Assess the need for changes to standard engineering practices to account for adaptation to climate change.
  - Initiate an education and outreach program to share results of this assessment with practitioners and decision makers.

An important point made in the report is that many of the potential impacts of climate change can be alleviated through improved system preservation activities and that climate change is only one factor that diminishes resiliency. "In recent years, concerns have been raised in Canada about the present levels of maintenance and future needs for infrastructure. . . . Climate change is likely to intensify the engineering vulnerability if current levels of maintenance continue. Properly maintained infrastructure enables the infrastructure and its components to function as designed, which includes accounting for changing climate events" (PIEVC 2008, p. 68).

Canada's Confederation Bridge—an 8-mile (13-kilometer) bridge between Borden, Prince Edward Island, and Cape Tormentine, New Brunswick—is an example of a completed project that took climate change into account during the planning and design phase. The bridge, which replaced an existing ferry connection, consists of a high-level two-lane road structure built on piers over the entire crossing of the Northumberland Strait. It provides a navigation channel for ocean-going vessels with vertical clearance of about 164 feet (50 meters). During the planning and design process, which was begun in 1985, sea-level rise was recognized as a concern. So that vertical clearance could be maintained into the future, the bridge was built 1 meter higher than was currently required to accommodate sea-level rise over its hundred-year lifespan. The bridge opened to traffic in 1997.

Scotland

The Scottish Road Network Climate Change Study also emphasizes this point in its discussion of the impacts of predicted climate change factors on the road network. The impact of heat on roadway rutting is frequently mentioned as a climate change concern. However, the report observes that "most rutting problems on the trunk road network are the result of pavement failure due to the volume of heavy goods vehicles" (Scotland Ministry of Transport 2005, p. 62). Impacts of roadway flooding due to increased amounts or intensity of rainfall are also an often-mentioned climate change concern. But, as the report notes, "the most common cause of flooding in areas where drainage is present is due to detritus washing into the system, resulting in partial or complete blockage" (p. 65). The report posits that "The effective maintenance of water-courses and ditches is essential to the operation of culverts and it is recommended that measures to target areas where known problems exist through preemptive clearing of detritus in advance of predicted heavy rainfall should be considered by all maintaining authorities" (p. 68). It also recommends, given the expected changes in rainfall, that the design storm be amended from a return period of between 1 in 100 years to 1 in 200 years (p. 67).

The Scottish Road Network Climate Change Study was the only report that discussed the impact of a lengthened growing season on the roadway network. It notes that in recent years it has been necessary to cut roadside grasses three times a year, up from two cuts a year. At most locations, landscape maintenance requires traffic management, which affects the traveling public. To offset the potential effects of a longer growing season, "it is recommended that slow-growing elements are used where appropriate, in order to minimize the extent of cyclic maintenance required" (Scotland Ministry of Transport 2005, p. 63–64).

The report also notes that many roadway risks associated with severe weather, which is predicated to increase under climate change scenarios, cannot be completely eliminated through design but should be addressed through ongoing road user education. These include conditions that result in poorer skidding resistance (such as heavy rains, roadway flooding, and winter conditions); reduced visibility due to fog; and unexpected forces being applied to vehicles in high-wind conditions. The report suggests that "ongoing road user education is an essential component in raising the awareness of the need to modify behavior during severe weather events. It is also considered that the provision of relevant information to road users in respect of such events would assist in encouraging modified behavior" (Scotland Ministry of Transport 2005, p. 76). In fact, the only condition in which large-scale adaptation strategies are suggested relates to coastal flooding situations and even then it proposes other approaches—including user education—first. "Areas at risk may then be addressed through a combination of warning signage, edge strengthening, or introducing sea-defenses. In extreme cases, consideration could be given to whether re-routing is appropriate. It is also recommended that any new projects proposed in low-lying areas should be reviewed with respect to these risk factors, to enable appropriate decisions to be taken at the design stage" (p. 75).

5.4.3 Asset Management Systems and Climate Change Adaptation

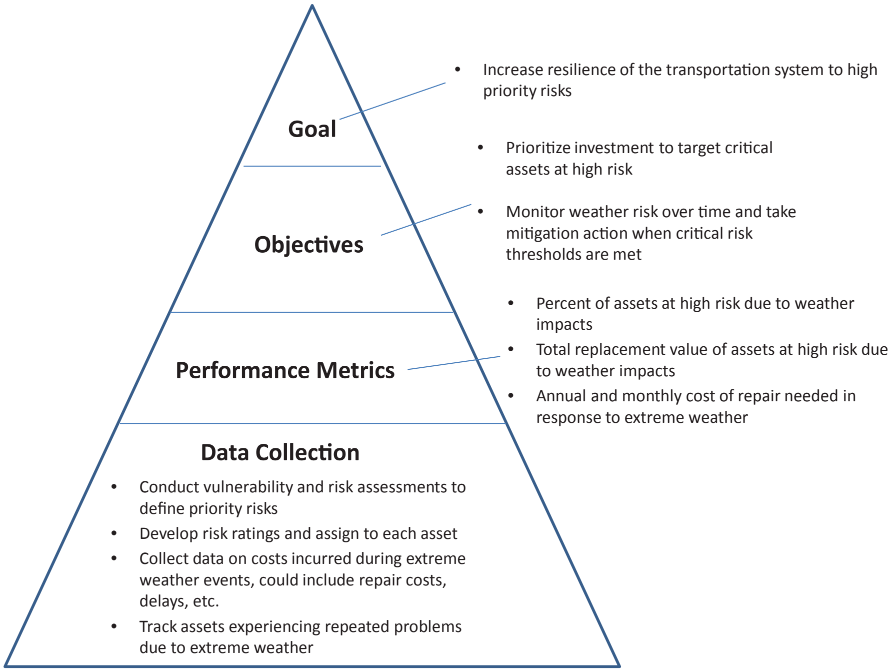
Transportation asset management (TAM) is defined as "a strategic approach to managing transportation infrastructure . . . focusing on business processes for resource allocation and utilization with the objective of better decision making based upon quality information and well-defined objectives"(AASHTO 2011). As agencies increasingly adopt TAM strategies, opportunities exist to integrate consideration of weather risk into TAM objectives, data collection, performance measurement, monitoring, and resource allocation decisions. Over time, the integration of weather and climate information into TAM will help agencies make targeted investments or allocation decisions to increase the resilience of the network and of individual assets to extreme weather events (Meyer et al. 2012b). State DOTs have long planned for fluctuations in the cost and timing of construction, availability of funding, and development of new regulations. However, extreme weather risk deserves special consideration because certain types of extreme weather are becoming more frequent and intense.

Figure II.14 shows how extreme weather and climate change considerations could be incorporated into an asset management goals structure. No significant restructuring of the TAM framework is needed to integrate climate change/extreme weather considerations into asset management systems. The spatial nature of much of the data used in TAM systems, combined with the results of risk analysis, can provide DOT officials with good indications of where potential problems exist.

A more detailed discussion of integrating climate change and extreme weather considerations into asset management systems can be found in the Practitioner's Guide (Part I of this volume) and in Meyer et al. (2010). In addition, two of the climate adaptation pilot studies supported by the FTA focus on the integration of climate change onto transit asset management systems.

5.5 Summary

This chapter has described the different types of climate change impacts that are likely to affect the nation's road system, both in terms of road design and operations/maintenance. The



Source: Meyer et al. (2012b).

Figure II.14. Integration of extreme weather concerns into asset management.

impacts are wide ranging, as are the types of adaptation strategies that can be considered. As shown in the Vermont case, and indeed in examples from other states, climate change and extreme weather events can be considered in many of the traditional agency functions—planning, environmental analysis, design, infrastructure retrofit, construction, operations, maintenance, emergency response and public outreach and communications. Of particular interest is the potential that asset management systems have in serving as a foundation for considering climate change impacts and needs as part of an agency's decision-making process. By considering asset management systems for such a platform, an agency puts in place an approach that is already well established in most transportation agencies and that allows climate change and extreme weather factors to be placed within a decision-making context that is familiar to agency officials.

CHAPTER 6

A Focus on Risk

6.1 Introduction

Most agencies that are concerned about adaptation begin by conducting a risk assessment of existing assets. Most of these risk assessments remain largely qualitative and based on professional judgment. This will likely remain the case until more probabilistic climate projections become available. Some risk assessments to date have shown the highway system to have only modest vulnerabilities to climate change. Others have indicated enough cause for concern to recommend that action be taken. Whether an agency chooses to take action depends on their fiscal and political capacity to effect change and their level of tolerance for risk. It is quite possible that separate agencies, facing the same risks, might choose very different courses of action, especially absent any set of national or industry standards.

The Practitioner's Guide (Part I of this volume) devotes a chapter to risk assessment tools and approaches and will not be repeated here. However, the following sections provide an overview of how risk can be viewed in the context of climate adaptation planning.

6.2 Risk Assessment Defined

An asset is vulnerable to climatic conditions if these conditions (such as intense precipitation and extreme temperatures) and their aftermath (such as a flood exceeding certain stages and consecutive days of higher than 100°F temperatures) result in asset failure or sufficient damage to reduce the asset's functionality. The vulnerability can thus be measured as the probability that the asset will fail given the occurrence of climate stressors (e.g., "there is a 90 percent chance the bridge in its current condition will fail with a 500-year flood"). Vulnerability primarily focuses on the condition of the asset.

Climate-related risk is more broadly defined in that risk can relate to impacts beyond simply the failure of the asset. It relates to the failure of that asset in addition to the consequences or magnitudes of costs associated with that failure (Willows and Connell 2003). In this case, a consequence might be the direct replacement costs of the asset, direct and indirect costs to asset users, and, even more broadly, the economic costs to society given the disruption to transportation caused by failure of the asset or even temporary loss of its services (e.g., a road is unusable when it is under water). The importance of broader economic costs to the risk analysis should not be underestimated. For example, if a bridge is located on the only major road serving a rural community and there is a possibility that the bridge could be washed out with major storms, the measure of consequence should include the economic impacts of isolating that community for some period of time while the bridge is being replaced.

Putting it all together, the complete risk equation is thus:

$$\begin{aligned}\mathit{Risk} = {} & \mathit{Probability\ of\ Climate\ Event\ Occurrence} \\ & \times \mathit{Probability\ of\ Asset\ Failure\ Given\ a\ Climate\ Event} \\ & \mathit{Occurrence} \times \mathit{Consequence\ or\ Costs}\end{aligned}$$

The risk equation shows that low-probability climate events (e.g., a Category 5 hurricane hitting the community) with high probabilities of asset failure and high consequence costs could still have high risk scores. Likewise, events with lower consequence costs, but greater probability of occurrence or conditional failure, could lead to similarly high risk scores. Most transportation-related climate change risk assessments performed to date have embraced this general risk conceptualization involving likelihoods of climate events occurring, probability of asset failure, and magnitude of the consequence.

According to the FHWA, "a risk assessment integrates the severity or consequence of an impact with the probability or likelihood that an asset will experience a particular impact. To determine consequence, transportation agencies may wish to consider the level of use of an asset, the degree of redundancy in the system, or the value of an asset (in terms of cost of replacement, economic loss, environmental impacts, cultural value, or loss of life)" (FHWA 2012a). The FHWA's conceptual framework (see Figure 4) incorporates a risk assessment component. The risk analysis is to be conducted on assets of high importance and to consider only those changing climate variables where there is either (1) a high likelihood and high magnitude of impact, (2) a high likelihood but low magnitude of impact, or (3) a low likelihood but high magnitude of impact. The vulnerability of each important asset is then to be evaluated based on how it has responded to historical changes in the climate variable in question and to associated extreme weather events. The costs of any repair or service disruptions are to be noted and a determination made as to the capacity of the particular asset to withstand the projected future changes in the climate stressor. From here, important assets that history indicates have a medium or high vulnerability to projected climate changes are carried forward for further risk analysis. Low-vulnerability assets are to be noted and marked for future monitoring.

The FHWA framework identified three characteristics of asset vulnerability that are key to understanding the level of risk attached to particular climate stresses for specific assets—sensitivity, exposure, and adaptive capacity.

6.2.1 Sensitivity

One of the first steps in a risk analysis is determining how an asset fares when faced with different climate stressors, called "sensitivity." Asset condition would be expected to be an important determining factor to an asset's sensitivity to stresses. In the cases of sea-level rise, storm surge, or riverine flood inundation, sensitivity is likely to be relatively straightforward and determined by the key thresholds where facilities become inundated. For bridges, the minimum elevation of the critical elements such as low points of approach roadways or deck or low chord elevations of the bridge could be used to help with this assessment. The sensitivity of rails and pavements to extreme heat and the sensitivity of bridges to strong winds would likely require close coordination with asset owners to ascertain critical thresholds.

6.2.2 Exposure

Once sensitivity is defined, the exposure of the asset to the climate stresses projected for the region given different emission scenarios needs to be determined. For most of the climate stressors, exposure could be determined through a GIS analysis overlaying the transportation network onto the climate projection information. The degree to which an asset is exposed to different stresses would be assessed. This might consist of the maximum depth of flooding or, for temperature and wind stressors, how high over the facility's sensitivity threshold the projected future value is. Whether the facility was affected by any recent extreme weather events would also be flagged.

When considering exposure to permanent sea-level rise, storm surge, and riverine flooding inundation, special care should be taken to ensure that inundation could realistically occur at each facility and that false positives (e.g., bridges and roadways that are elevated and thus not likely affected by rising water levels) are identified. This will likely require a visual assessment of the key assets in the GIS data sets. Special approaches will also be required for tunnels because a straightforward GIS analysis of subterranean road and transit lines will not necessarily capture the possibility of water entering tunnels through ventilation systems and other access points.

6.2.3 Adaptive Capacity

Adaptive capacity, the ability of the transportation facility and network to cope with the consequences of exposure, is another key component of vulnerability. An important concept when assessing adaptive capacity is the redundancy of the transportation network; the greater the network redundancies, the greater the ability of the transportation system to absorb the loss of use of a given facility affected by climate stressors (i.e., the higher its adaptive capacity). On the highway network, redundancies may take the form of alternate routes that people can use to detour around compromised facilities. A typical approach to analyzing the redundancy component of adaptive capacity is to consider the daily cost of the additional travel time required by different types of facility users (e.g., drivers, bus and rail passengers, freight movements) when taking an alternative mode or detour route. The daily cost of additional travel time would most often be assessed with the aid of a regional travel demand model, which covers the entire project study area based on network detail. By removing the climate stressor–compromised links in the model, the optimal detour routes for travelers and the implications of those detoured trips on congestion can be ascertained. Short-term transportation recovery mitigation plans, such as reconfigured highway routings and transit service plans, could be directly modeled with the model. The model would forecast travel demand changes, including diversions to alternate highway routes and transit facilities, quantifying the implications of the revised travel patterns in terms of congestion impacts, travel times, and other user costs. This would highlight routes that, if affected, might have significant ripple effects throughout the network.

Another component of adaptive capacity is how long it takes to restore service to the facility once it has been compromised: the longer the restoration time the lower the adaptive capacity and the higher is that facility's vulnerability. Restoration time (to be measured in days) can be considered a multiplier to the additional user costs associated with detours. In other words, each day of expected downtime can be multiplied by the user costs to arrive at a better representation of user costs if there is a failure. Restoration times might be as little as a day or two for temporary flooding where permanent damage is not expected or weeks for assets like tunnels and electronic rail infrastructure that require major restoration efforts.

Replacement costs are the final component of adaptive capacity that needs to be considered in the vulnerability analysis. The costs to replace or repair a compromised asset are an important component of the adaptive capacity from an asset owner's perspective. Thus, all else being equal, larger transportation investments with higher replacement/repair costs can be considered to have a higher vulnerability worthy of greater prioritization for adaptive action. High-level replacement and repair costs for each facility can be estimated based upon standard cost-estimating procedures, historical experiences, and consultation with asset owners. These repair and replacement costs would be added to the user costs discussed previously to arrive at a vulnerability score (in dollars) for each asset. If this analysis is being used to compare vulnerability levels among a number of assets (to determine priorities), a normalization scheme could be employed to ensure that the scores are comparable across facilities.

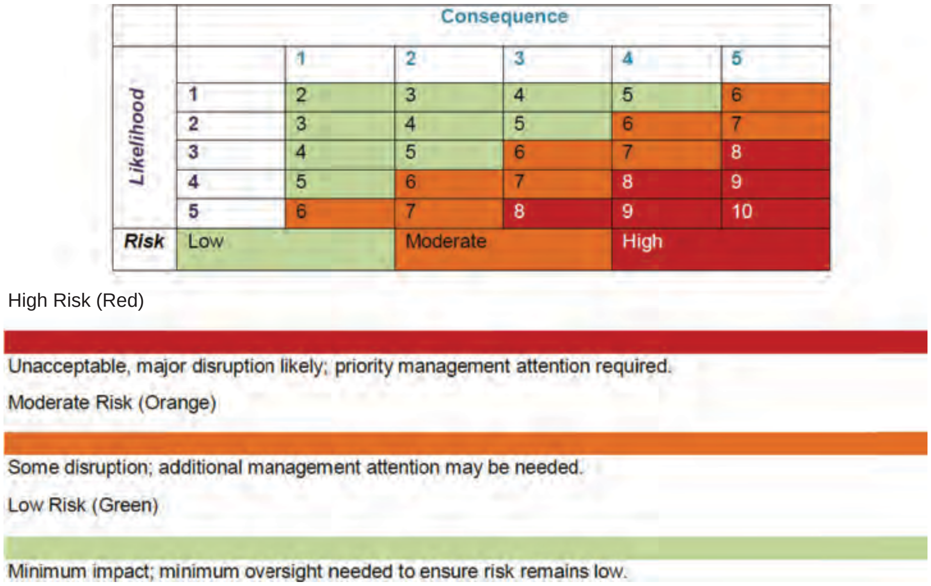
Adaptation options can then be considered for high- or medium-risk assets while low-risk assets are given lower priority for the time being.

6.3 Approaches to Risk Assessment

Several adaptation plans illustrate some of the tools and processes for risk assessment that have been developed by various states and localities. Both King County, Washington, and New York City provided tools primarily meant to assist staff in their own agencies in structuring risk and vulnerability assessments but also designed to be generic enough to be used by other localities. For instance, King County's *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* provides a checklist and recommendations for conducting vulnerability and risk assessments (Center for Science in the Earth System and King County 2007). Other agencies have already made use of these tools—most notably, *A Framework for Climate Change Adaptation* in Hawaii was based directly on the King County guidelines.

The New York City Panel on Climate Change's *Adaptation Assessment Guidebook* also contains tools to help stakeholders. For instance, like King County's *Preparing for Climate Change*, the *Adaptation Assessment Guidebook* provides sector-specific infrastructure questionnaires to guide the assessment process and create an inventory of infrastructure at risk to climate change impacts. It also provides a risk matrix, a tool to help categorize and prioritize the risk assessment findings by facility, based on the probability of the climate hazard, likelihood of impact, and magnitude of consequence.

These and similar studies resulted in a qualitative assessment of the risks associated with specific transportation assets. Figure II.15 from *Adapting to Rising Tides* is a good example of how this approach is portrayed (Metropolitan Transportation Commission, Caltrans, Bay Conservation and Development Commission, 2011). Such a framework has been used to conduct initial, high-level risk assessments that identify the major climate drivers most likely to impact a given agency's infrastructure, the types of infrastructure most vulnerable, and discuss the kinds of impacts that might be expected.



		Consequence				
		1	2	3	4	5
Likelihood	1	2	3	4	5	6
	2	3	4	5	6	7
	3	4	5	6	7	8
	4	5	6	7	8	9
	5	6	7	8	9	10
Risk	Low		Moderate		High	

High Risk (Red)

🟥

Unacceptable, major disruption likely; priority management attention required.

Moderate Risk (Orange)

🟧

Some disruption; additional management attention may be needed.

Low Risk (Green)

🟩

Minimum impact; minimum oversight needed to ensure risk remains low.

Source: Metropolitan Transportation Commission, Caltrans, Bay Conservation and Development Commission (2011).

Figure II.15. Example risk assessment from the San Francisco Bay Area.

Most of the risk assessments reported in the literature have primarily focused on the water-related impacts: sea-level rise, flooding, intense tropical storms, and intense precipitation. Threats to evacuation routes have also been assessed in many coastal locations. Fewer have focused on temperature itself as a major issue for highway systems, although some have included air quality and heat island concerns. For instance, the transportation vulnerabilities identified in Hawaii include threats to transportation infrastructure (evacuation routes) due to sea-level rise and storm flooding; weakening of infrastructure due to repetitive and prolonged stress (dams, roads, bridges, tunnels, storm drains); and submersion of vital transportation infrastructure due to sea-level rise and flooding. Alaska identified a unique set of vulnerabilities that do not exist in the other 49 states, particularly infrastructure damage from permafrost thaw and severe coastal erosion from lack of sea ice armoring.

The emphasis on water-related risk assessment is perhaps not surprising. These parameters are both more pressing and somewhat easier to identify for most agencies due to the (relative) simplicity of comparing infrastructure elevation to sea-level rise scenarios. For instance, California's Preliminary Transportation Assessment identified the number of miles of highway that would be inundated by a 55-inch sea-level rise, by county and road.

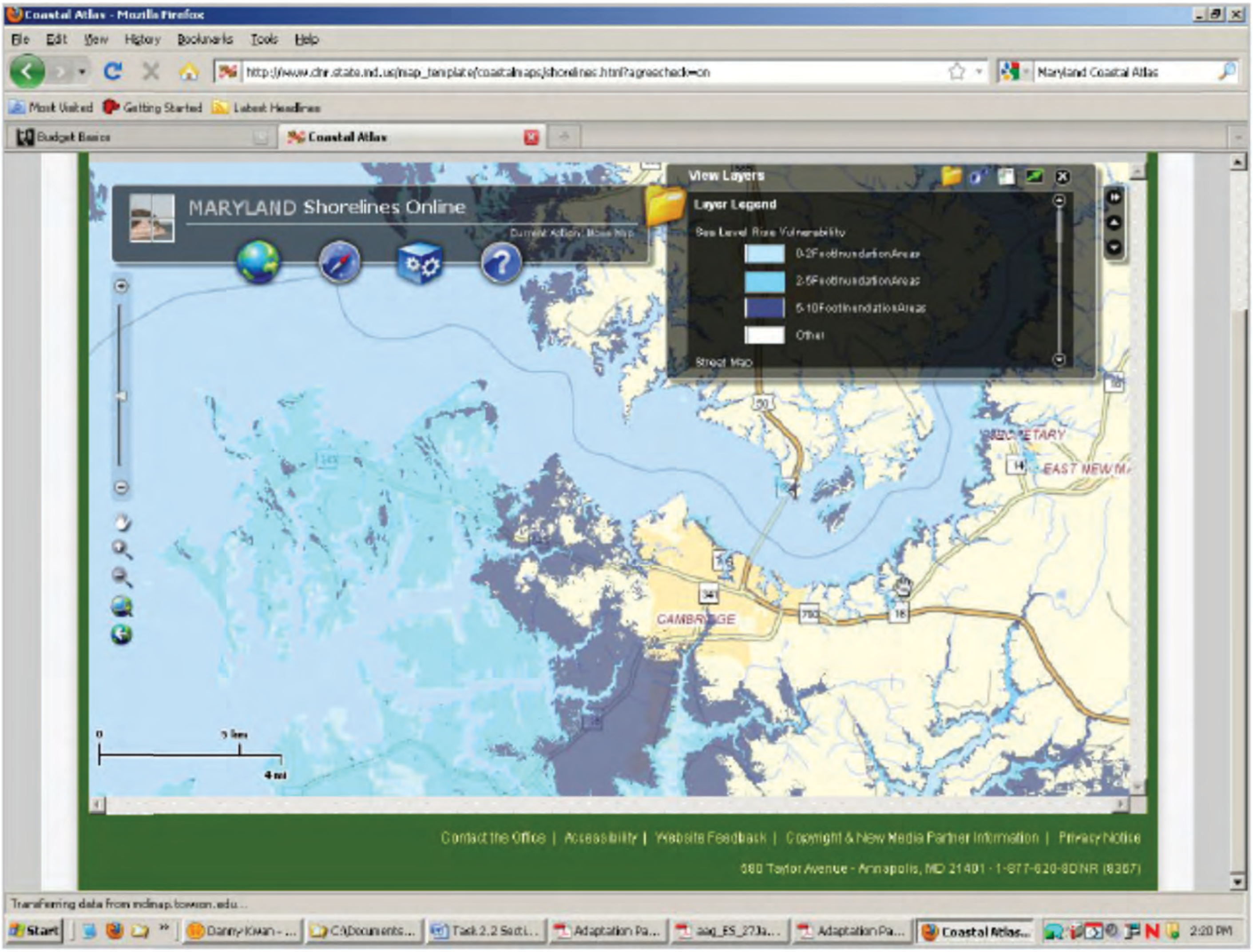
Few agencies have gone to the point of systematically inventorying their assets to identify how each transportation link or facility will be affected by climate change. Nonetheless, as states have finished the initial round of adaptation planning, some have begun the process of identifying vulnerabilities to their transportation infrastructure in a more comprehensive manner. For instance, California and Maryland DOTs have conducted in-depth assessments of the vulnerability of their road systems. Washington State DOT (WSDOT) has also conducted a vulnerability assessment of WSDOT-owned infrastructure.

The process of identifying vulnerable assets and then assigning risk values to them is likely to be a collaborative process, including a range of participants (Slater 2011). Maryland provides an illustrative example of a state implementing the systems needed for a more detailed risk inventory. It is one of the first states to begin systematically inventorying the vulnerability of its transportation assets to climate change, beginning with vulnerability to sea-level rise. Sea-level rise is an initial priority for Maryland's adaptation plan because of that state's particular vulnerability: it has more than 4,000 miles of coastline, much of it low-lying land on the Chesapeake Bay at risk to inundation (in fact, in the past century several islands in the Bay disappeared under the rising water levels). As a result, the Maryland adaptation plan recommended the integration of coastal erosion, coastal storm, and sea-level rise impacts into existing state and local policies and programs.

To that end, the state has pursued several initiatives in partnership with universities, non-government organizations (NGOs), and NOAA. For instance, the Coast-Smart Communities Initiative provided funding and technical support to towns in coastal counties to prepare for sea-level rise, coastal erosion, and storm inundation. More concretely, the state has developed a high-resolution LiDAR data set to allow development of sea-level rise inundation models along its coastlines. This data set has been made available to the public as the Maryland Coastal Atlas, including maps of sea-level rise vulnerability areas (viewable with the Coastal Atlas Shoreline mapping tool). State-wide Sea-Level Rise Vulnerability Maps have been created for 14 coastal counties, depicting lands at potential risk. These maps show lands at three elevations (i.e., 0 to 2 feet, 2 to 5 feet, and 5 to 10 feet) above mean sea level. The use of LiDAR data allowed the Maryland Coastal Atlas to map sea-level rise with more precision than was found in two previous reports on mid-Atlantic sea-level rise by the U.S. Climate Change Science Program (CCSP) or U.S. DOT, making it the most advanced sea-level rise resource for the mid-Atlantic region (see Figure II.16).

Not all locations possess these data and can do analyses at this resolution: the CCSP reports that it may be some time before the rest of the mid-Atlantic region has comparable LiDAR elevation data that are suitable for detailed assessments of sub-meter increments of sea-level rise. One potential use of the mapping tool is to identify coastal areas subject to coastal flooding from storm inundation and sea-level rise for long-range planning, floodplain management, and emergency management. Using this data set, the Maryland State Highway Administration is currently building a new shoreline data set as a polygon for GIS mapping to determine which assets are located within the zone of inundation. These data will eventually be compiled into an overall Maryland DOT assessment of Maryland's critical transportation facilities and the system's vulnerability to projected sea-level rise and extreme weather damage.

In addition, the Maryland State Highway Administration and the Maryland Transportation Authority (which has responsibility for the state's toll facilities) are in the process of developing a joint climate change adaptation policy and an accompanying implementation strategy. The overarching policy goal of the effort is to continue to cost-effectively maintain the safety and serviceability of Maryland's highway system as the state's climate changes. This policy will be implemented with a four-part strategy that includes (1) taking practical operations, maintenance, and administrative actions to respond to and limit damage from extreme weather events that are already occurring and may worsen with time; (2) developing a stronger understanding of the longer-term threats to the state's highway network posed by a changing climate; (3) developing approaches for adapting existing infrastructure to climate



Source: Maryland Coastal Atlas Shoreline mapping tool.

Figure II.16. Sea-level rise analysis in Maryland.

changes as an improved understanding of risks develops; and (4) considering adaptation for new projects to increase their resiliency to potential climate impacts.

Seventy detailed action items have been developed to implement this four-part strategy. These include a number of “no-regrets” operations actions that will improve the agencies’ response to severe weather events. Operations actions include, among other things, better planned and managed detour routing and installing battery back-up power at all signals that would require a traffic officer if there was an outage. The action items also include maintenance activities that, to the extent possible, prevent impacts from occurring in the first place. These include electronic tracking and mapping of work orders to identify areas of recurring problems and streamlining environmental permitting to allow for quicker debris removal in culverts and underneath bridges. Other action items call for conducting risk analyses of existing facilities throughout the state (in coastal areas and beyond) and the development of procedures for incorporating adaptation into the siting and design of new facilities and major rehabilitations. Responsibility over each of the 70 action items has been delegated to specific departments within the DOT ensuring that adaptation will become an agency-wide concern.

One of the most recent tools developed for sea-level rise analysis comes from the Florida DOT and is called the Florida Sea-Level Scenario Sketch Planning Tool (Thomas et al. 2013). The tool is intended to be used primarily at the state and regional levels. The sea-level projection rates were considered “low,” “intermediate,” and “high.” Low rates were estimated by simply extending historical rates of sea-level rise into the future target years (2040, 2060, 2080, and 2100). Intermediate and high projected rates were taken from scenarios developed by the USACE. The estimated sea-level rise anywhere along the Florida coast for the target years was tied to the expected increase in sea levels at existing tidal gauges. A state-wide digital elevation model was developed by combining information from four existing digital elevation model databases for the state. The transportation database layer was developed from the state DOT's existing road and bridge inventory. Inundation scenarios were then created by superimposing the sea-level rise elevation with the digital elevation model (Figure II.17), and vulnerable transportation facilities were then identified by tying the rising water levels to the elevation of transportation facilities.

This tool provides an important capability to state and local officials who want to identify vulnerable areas and facilities in their jurisdiction. Given the GIS platform of the tool, eventually the analyses can be conducted that link inundation areas with critical community and economic areas, populations of concern, high-value facilities (such as emergency management offices or hospitals), and evacuation routes. This would add the element of risk analysis into the tool capability.

Internationally, a synthesis by Wall and Meyer (2013) showed that risk frameworks were almost always based on internationally or nationally adopted procedures for risk assessment. Independent and private-sector transportation organizations (i.e., port authorities, airports) frequently reported that enterprise risk management was already a part of their existing business management activities and that climate change adaptation planning would be incorporated into these existing practices. For example, in the United Kingdom, both the Port of Dover (2011) and NATS (2011)—an air traffic control organization—noted that the International Organization for Standardization standard ISO 31000:2009, *Risk Management—Principles and Guidelines*, was used in developing their risk management programs.

In Canada, the Ontario Ministry of Municipal Affairs & Housing (Bruce et al. 2006) and Natural Resources Canada (Canadian Institute of Planners 2011) both reported that the standard CAN/CSA-Q850-01, *Risk Management: Guidelines for Decision Makers*, was used in developing their frameworks; the Halifax Regional Municipality (Dillon Consulting and de Romilly & de Romilly Limited 2007) used an earlier edition of the same standard, as well as CAN/CSA-Q634-M91, "Risk Analysis Requirements and Guidelines."

Frameworks in Australia and New Zealand (CSIRO et al. 2007, Gardiner et al. 2008, Gardiner et al. 2009) were predominantly informed by AS/NZS 4360:2004, *Risk Management*, and the superseding standard AS/NZS 31000:2009. This latter standard is also specified as ISO 31000:2009, which was used in the development of the *Risk Management for Roads in a Changing Climate* framework in the European Union (Bies et al. 2010).

Australia's *Climate Change Impacts & Risk Management: A Guide for Business and Government* is a good example of how risk is viewed in other countries. This guide recommends that risk identification, analysis, and evaluation be conducted

(a) Florida inundation from sea-level rise, 2060 (approximately 28 inches)

(b) Florida inundation from sea-level rise, 2100 (approximately 62 inches)

Source: Inundation mapped using the USACE High Curve (Circular EC 1165-2-12) and NOAA Key West tide gauge data, Mean Higher High Water; Inundation map: University of Florida GeoPlan Center, 2013; Imagery (background image): Esri, DigitalGlobe, GeoEye, I-Cubed, USDA, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure II.17. Florida inundation from sea-level rise, 2060 and 2100.

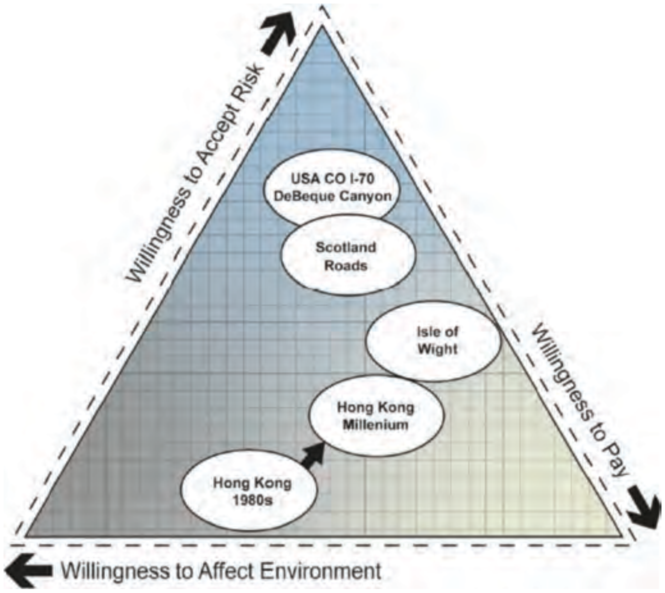
by risk element, that is, discrete elements or areas facing the organization (Commonwealth of Australia 2006). This can provide focus to the discussion and help participants more efficiently look at and understand potential risks. The recommended process is as follows:

Step 1: Brainstorm risks associated with the element until the main issues are felt to have been exposed.
Step 2: Taking each risk in turn:
  a. Identify any existing controls (features of the environment, natural and manmade structures and mechanisms, procedures and other factors) that are already in place and tend to mitigate the risk;
  b. Describe the consequences the risk would have if it was to arise, given the controls, and in each of the scenarios under consideration;
  c. Describe the likelihood of suffering that level of consequence, again given the controls, in each of the scenarios under consideration;
  d. Assign an initial priority in each scenario based on the likelihood and consequence of the risk; and
  e. Where two or more scenarios are being considered, consider adjusting the priority in recognition that some scenarios are less likely to occur than others.
Step 3: Return to Step 1 for the next key element.

Climate Change Impacts & Risk Management provides six principles (gleaned from climate change adaptation processes) for treating climate change risk:

- Achieve balance between climate and non-climate risks
- Manage priority climate change risks
- Use adaptive management
- Look for win-win or no-regrets treatment options
- Avoid adaptation constraining decisions
- Review treatment strategy

Another perspective on risk and adaptation strategies is presented in Figure II.18, the Willingness Diagram from the *Scottish Road Network Landslide Study* (Winter et al. 2008). This figure shows the trade-offs between willingness to accept (or tolerate) risk, willingness (and/or ability) to pay, and willingness to alter the environment in the pursuit of lower risk. How a managing agency views each one of these factors will influence where a particular project falls in the triangle. At present, when it comes to roadway infrastructure, projects seem to fall at the upper point of the triangle—a high willingness to accept risk and a low willingness to pay. This may be partly driven by the fact that the risks seem low and there are low-cost, incremental approaches available.



Source: Winter et al. (2008).

Figure II.18. The risk domain from Scotland's landslide study.

Of interest to the consideration of risk in adaptation planning, the Wall and Meyer synthesis noted that "the way risk is perceived and characterized was the second most commonly listed limitation or barrier (after data limitations). Numerous agencies noted that it was difficult to define acceptable levels or risk, relevant types of risks, and the critical thresholds of risk" Wall and Meyer (2013). Furthermore, in the decision-making process, difficulty was noted in linking the immediate need for action with risks that are perceived to be of long-term or distant consequence. Effectively linking risk levels to the decision-making process was further compounded by what many agencies discussed as the qualitative treatment of risk, that is, a reliance on expert opinion and risk matrices.

Chapter 4 of the Practitioner's Guide (Part I of this volume) discusses different approaches for conducting risk assessment in climate adaptation planning.

6.4 Summary

This chapter has presented an overview of one of the most important concepts in adaptation planning. Risk assessment allows transportation officials to identify which vulnerable assets are most important from both the perspective of transportation system performance and to an asset's contribution to larger goals, such as economic activity and public safety. Risk is defined as the probability of climate event occurrence multiplied by the probability of asset failure multiplied by the consequence or costs of failure. Thus, as noted in the chapter, a high-risk asset could be one in which one or more of these factors have high values. For example, an asset with a low probability of occurrence and low probability of failure would still achieve a high level of risk if the consequences of failure are traumatic or result in huge economic costs. By considering these factors and the role that assets play in the transportation systems, transportation officials can identify where investment should occur to limit the risk associated with such failure.

Although the definition of risk above includes some indication of probable occurrence, in reality, such probabilities are hard to formulate, especially when considering that the occurrence in question might not be real until many years into the future. To account for this uncertainty, most studies have relied on qualitative or subjective assignment of risk. Thus, “high,” “medium,” or “low” is often used to indicate the level of risk associated with individual assets. Even those approaches considered more quantifiable use ordinal rankings of values, that is, “1,” “2,” or “3” to indicate relative risk. The intent of these approaches is straightforward—to provide decision makers with some sense of where investment in the transportation system would provide the greatest reduction in risk associated with climate change–related disruptions.

CHAPTER 7

Extreme Weather Events

7.1 Introduction

During the course of this research, the United States experienced several extreme weather events that caused severe disruption to the transportation system and in several cases significant damage (e.g., Superstorm Sandy, Hurricane/Tropical Storm Irene, extreme heat events in the Midwest and Southwest, flooding in the Midwest, and unexpected major snow storms in New England and the Mid-Atlantic). Because of these events, many transportation agencies and related associations (such as the AASHTO) have focused attention on how agencies could prepare for, manage agency operations during, and recover from weather events that exceed normal ranges of severity and impacts. Although climate science does not yet definitively link these extreme weather events to a changing climate, such events are of the kind that many climate scientists believe will characterize future weather more so than evident today. This chapter examines some of the recent experience with extreme weather events and provides a checklist of steps transportation agencies can take to organize themselves for dealing with the transportation-related impacts of such events.

7.2 Extreme Weather Events and Transportation Agency Operations

According to the FHWA, extreme weather events refer to “rare weather events that usually cause damage, destruction, or severe economic loss. Extreme weather events include heavy precipitation, a storm surge, flooding, drought, windstorms, extreme heat, and extreme cold.” (FHWA 2012a). Transportation agencies have been dealing with extreme weather events ever since agencies were given responsibilities for managing the operations of transportation systems. A great deal of experience exists in the transportation profession on how to anticipate the disruptions due to weather events and how to provide capabilities so that the transportation system can recover from any disruptions.

However, state transportation officials at a 2013 symposium on extreme weather events and related transportation impacts noted that in many parts of the country the frequency and severity of such events have seemed to increase, infrastructure damage and community costs have risen, the impact of recovery costs on maintenance budgets and on regular operations activities continues to become more significant, and perhaps most importantly public expectations of a transportation agency’s ability to recover the transportation system quickly and efficiently have increased greatly (AASHTO 2013). In several instances, the recurring pressures on state transportation officials to prepare for, manage, and recover from extreme weather events have caused organizational change, development of new management responsibilities (e.g., emergency management officials), modification of standard operating procedures, and staff training in managing and administering recover efforts.

A transportation agency’s role in an extreme weather event can be divided into three major phases: pre-event planning, management of the transportation system during the extreme event, and post-event activities and lessons learned. Table II.6 shows the types of strategies and actions that state transportation agencies have taken in response to extreme weather events during each of these phases. These strategies and actions were distilled from case studies of agencies’ responses to extreme weather events presented at the AASHTO symposium mentioned earlier, as well as presentations made by transportation officials in other meetings.

As reported in the Practitioner’s Guide (Part I of this volume), Lockwood (2008) suggests that changing climatic and weather conditions lead to several actions that transportation agencies should consider:

- “Improvements in surveillance and monitoring must exploit a range of potential weather-sensing resources—field, mobile, and remote.
- “With improved weather information, the more sophisticated, archival data and integration of macro and micro

Table II.6. State transportation agency strategies for extreme weather events.

Strategy or Action	State
Pre-event Planning	
• Develop timeline of likely agency response actions. • Establish clear command and control structure for emergency response; develop lines of authority with other agencies.	Arizona, Vermont
• Develop an emergency response manual, inventory lists, contact information, and three-tiered response and distribute "smart technology" with required forms and software in order to be better prepared for the next emergency. • Compile a contractor registry database, develop a standardized electronic contract processing system, develop an emergency administrative packet for incident command centers, develop an emergency administrative packet for contractors, develop an emergency waiver process, explore alternative emergency contracting processes, and review and standardize the process for paying contractors. • Develop and maintain an active distribution list of cell phones, explore the use of cloud technology, formulate a recommendation for data storage during emergency response, explore and develop connectivity with data sets, explore the use of information technology applications (511, Google, etc.) for emergency response, develop a process to track equipment and materials from contractors, and standardize data collection and data integration.	Vermont
• Pre-purchase (e.g., traffic cones for police vehicles) and pre-position (e.g., replacement culverts).	Minnesota, Colorado
• Review administrative policies for staff activities (e.g., hotels/food/local transportation charges). • Develop contingency plans for specialized equipment (e.g., expanded number of contracts for critical roads, and essential supplies such as road salt for winter storms). • Improve agency-wide situational awareness of weather event and its impacts.	District of Columbia (D.C.)
• Increase emphasis on storm drainage maintenance and debris removal.	Colorado
• Increase public awareness of what they should do in an extreme weather event. • Partner with other agencies/conduct workshop on how to respond to extreme weather event.	Arizona
• Establish protocol for use of traveler warning strategies [e.g., 511 traffic information system (online and phone), overhead electronic message boards, Twitter and Facebook, wireless emergency alerts, mobile apps and real-time roadside alert systems].	Arizona, Iowa, Washington
• Provide emergency response training to agency staff.	Alabama, D.C., Vermont
• Coordinate with other states to establish multistate strategy for responding to weather events. • Implement maintenance decision support systems for extreme weather event planning.	Iowa, Michigan
• Establish clearly defined detour routes and detour route operations strategy.	Missouri, Washington
• Develop and/or understand evacuation procedures.	Iowa
During-Event System Management	
• Document actions taken and resources used (will be needed for post-event reimbursements).	Minnesota, New Jersey, D.C.
• Establish or use current incident command center. • Establish close coordination with law enforcement to close roads. • Have in place strategy for using resources that come from other jurisdictions. • Use tactical response teams to investigate seriously impacted areas. • Utilize a variety of communications strategies for traveling public and other stakeholders (e.g., media releases and interviews, internet announcements, e-mail alerts, local meetings and briefings, site impact tracking tool, and road closure maps on the internet).	Minnesota

Table II.6. (Continued).

Strategy or Action	State
During-Event System Management (continued)	
• Establish corridor DOT staff patrols to monitor road damage. • Prepare "Road Closed" signs and place them in consultation with law enforcement and communications specialists.	Colorado
• Utilize resources to provide real-time monitoring of extent of damage or threat (e.g., Minnesota used state police helicopter to monitor flood levels). • Use Google Earth with custom layers (inundation levels, LIDAR, historical imagery, etc.) (Iowa).	Iowa, Minnesota
• Engage the resource agencies, USACE, and the FHWA early and throughout the event. • Coordinate with emergency responders and keep them updated on closures and openings throughout the event. • Utilize an electronic Detailed Damage Inspection Report (DDIR).	Iowa
Post-event Recovery	
• Re-examine incident response plans and update based on experience. • Use project development and joint engineering/maintenance teams to perform early assessments of damaged infrastructure and to assess newly vulnerable areas (e.g., new erosion patterns due to fire impacts).	Minnesota, Colorado
• Conduct debriefs with key stakeholders. • Re-examine agency contingency plans in light of event response and document lessons learned. • Implement training programs for front-line responders (e.g., snow plow simulator training).	Arizona, D.C.
• Examine technology strategies that could be used to improve response efficiency (e.g., AVL monitoring of vehicle location). • Install monitoring technology to provide alerts to maintenance staff of weather-related threats (e.g., wireless connected rain gages). • Install roadside traveler alert systems.	Arizona, Colorado, D.C., Minnesota
• Examine standard operating procedures for both design and maintenance to determine if different approaches might be better (new design manual will be focused on risk-based design and slope designs are being redefined).	Vermont
• Expedited contract for inspection and reconstruction of major interchange. • Hire consultants to augment staff and reduce recovery time. • Understand and track the timing of a Presidential Disaster Proclamation; 180-day clock starts immediately. • Develop electronic "as-builts" that utilize survey-grade accuracy LIDAR to expedite future plan development (all survey control points on a major Interstate were lost in the flood).	Iowa

Source: AASHTO (2013).

trends will enable regional agencies to improve prediction and prepare for long-term trends.

- "This in turn can support the development of effective decision support technology with analyses and related research on needed treatment and control approaches.
- "The objective to be pursued would be road operational regimes for special extreme weather-related strategies such as evacuation, detour, closings, or limitations based on preprogrammed routines, updated with real-time information on micro weather and traffic conditions.
- "For such strategies to be fully effective, improved information dissemination will be essential—both among agencies and with the public, using a variety of media.
- "Finally, the institutionalization of the ability to conduct such advanced operations will depend on important changes in transportation organization and staff capacity as well as new more integrated interagency relationships."

As is seen in Table II.6, many state transportation agencies are implementing the actions suggested by Lockwood.

7.3 Summary

Extreme weather events have been receiving increasing attention from transportation officials for their disruptive impact on transportation system performance and more importantly for their consequences to agency operations. Although transportation agencies have decades of experience in responding to extreme storms, recent years have seen a larger than average number of record weather events that have significantly affected transportation systems, and have placed increasing demands on transportation officials to respond quickly and efficiently. This chapter presented actions and strategies that agencies can use in event pre-planning, event management, and post-event recovery activities. Many of these strategies have been used by several agencies, while others are unique to a state and extreme weather event context (e.g., Vermont's re-examination of design approaches for roads near rivers and streams). In all cases, however, they represent an assessment on the part of state transportation officials of what lessons can be learned from their experience with extreme weather events and how changes can be made to improve this response in future events.

CHAPTER 8

Conclusions and Suggested Research

8.1 Introduction

This chapter presents the major conclusions of this research study and recommends research topics that could further climate adaptation practice in the United States. The conclusions focus on the current practice of adaptation planning and likely future characteristics. The research project also produced recommended practice and guidelines found in the Practitioner's Guide (Part I of this volume) that are not repeated here.

8.2 Conclusions

The climate change adaptation field is in its infancy yet continues to evolve rapidly. In part caused by the occurrence of extreme weather events that surpass the damage and disruption seen in prior years, but also in recognition of a growing public acceptance that climate change is an issue that needs to be considered by policy makers, new approaches and techniques for assessing the threats it poses are being developed. In addition, initiatives on the part of federal and state agencies to identify and demonstrate new approaches to adaptation planning (e.g., the climate adaptation pilot projects sponsored by the FHWA and the FTA) have brought new tools and techniques to the profession. As more experience with these tools and techniques occurs, more transportation agencies can be expected to begin thinking about how climate change and extreme weather is likely to affect their operations and capital investments in the future.

Overarching conclusions from this research fall into four categories: context, climate change, adaptation diagnostic framework, and agency functions.

8.2.1 Context

- There is a growing understanding among researchers and highway officials that climate change and extreme weather events are a threat to many aspects of the highway system, which warrants spending resources to investigate the specific risks they pose. Still, many U.S. highway agencies have not yet taken any substantive adaptation planning actions.
- Both domestically and internationally, limited action has been taken "on the ground" thus far to build resiliency into the transportation system. Indeed, with some notable exceptions, much adaptation work remains at a planning or risk assessment level and has yet to be incorporated into the design of individual projects. This is likely to change in the near future as the risk assessment studies progress and as transportation officials begin to realize that in certain areas a changing climate could have significant impact on highway planning, design, construction, and operations/maintenance. It is noteworthy that in the aftermath of Superstorm Sandy, high-level officials in New York and New Jersey called for new ways of designing infrastructure such that resiliency is built into the system.
- The U.S. population will continue to grow with most of this growth occurring in urban areas and in parts of the country expecting notable changes in climate. The composition of this population will be very different than it is today, with more diverse populations and elderly in the nation's population mix. Significant levels of housing and corresponding development will be necessary to provide places to live and work for this population, with much of this development likely to occur in areas subject to changing environmental conditions. Increasing population growth will create new demands for transportation infrastructure and services, once again in areas that are vulnerable to changing climate conditions. The nation's highway system will be facing increasing demands for reconstruction and rehabilitation over the next 40 years (to 2050), which provides an opportunity to incorporate climate adaptation strategies into such efforts, if appropriate.

8.2.2 Climate Change

- Temperatures in the lower 48 states are projected to increase about 2.3°C (4.1°F) by 2050 relative to 2010. While all

U.S. regions are projected to increase in temperature, the amounts will vary by location and season. In general, areas farther inland will warm more than coastal areas, because the relatively cooler oceans will moderate the warming over coastal regions. In addition, northern areas will warm more than southern areas because there will be less high-latitude snow cover to reflect sunlight. More warming is projected for northern and interior regions in the lower 48 states than for coastal and southern regions.

- In general, the models project and observations also show that the Northeast and Midwest are likely to become wetter while the Southwest is likely to become drier. In addition, all the climate models project an increase in precipitation in Alaska. It is not known whether precipitation will increase in other areas such as the Northwest or the Southeast. While the models tend to show a drier Southwest and a wetter Northeast and Midwest, the differences across the models mean that forecasting exactly which localities become wetter or drier and where the transitions between wet and dry areas lie is not possible. Climate models tend to project relatively wetter winters and drier summers across most of the United States. However, this does not mean that all areas are projected to receive more precipitation in the winter and less precipitation in the summer. The models also project a larger increase in summer temperature than winter temperature.
- Extreme temperatures will get higher. This means that all locations will see increases in the frequency and duration of occurrence of what are now considered extreme temperatures such as days above 32°C (90°F) or 35°C (95°F). In the long run, the number of days below freezing will decrease in many areas, particularly southern locations.
- Precipitation intensities (both daily and 5-day) are projected to increase almost everywhere, although the largest increases tend to happen in more northern latitudes.
- Recent research has suggested that there will be fewer hurricanes, but the ones that do occur, particularly the most powerful ones, will be even stronger.
- Global sea levels are rising. Projections of future sea-level rise vary widely. The IPCC projects that sea level will rise 8 inches to 2 feet (0.2 to 0.6 meter) by 2100 relative to 1990. Several studies published since the IPCC Fourth Assessment Report, however, estimate that sea levels could rise 5 to 6.5 feet (1.5 to 2 meters) by 2100. Sea-level rise seen at specific coastal locations can vary considerably from place to place and from the global mean rise because of differences in ocean temperatures, salinity, and currents and because of the subsidence or uplift of the coast itself.

8.2.3 Adaptation Diagnostic Framework

- A diagnostic framework can be used to guide the steps in adaptation planning:
  - Step 1: Identify key goals and performance measures for adaptation planning effort.
  - Step 2: Define policies on assets, asset types, or locations that will receive adaptation consideration.
  - Step 3: Identify climate changes and effects on local environmental conditions.
  - Step 4: Identify the vulnerabilities of asset(s) to changing environmental conditions.
  - Step 5: Conduct risk appraisal of asset(s) given vulnerabilities.
  - Step 6: Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness, and defensibility of options.
  - Step 7: Coordinate agency functions for adaptation program implementation (and optionally identify agency/public risk tolerance and set trigger thresholds).
  - Step 8: Conduct site analysis or modify design standards (using engineering judgment), operating strategies, maintenance strategies, and construction practices.
- This eight-step process is inherently a multidisciplinary and collaborative one. It is not likely that a state transportation agency has internal staff capability on climate science. In most cases, these agencies have been working with the local university or the state climatologist in order to obtain such input. In many cases, the vulnerability and risk assessment process depends on local input on what is considered to be the most critical assets in an urban area. Or, perhaps more importantly, the actions taken by local communities and governments, such as land use approval and street/drainage design, could have significant impact on the ability of state assets to handle larger loads, and thus, there is a need for coordination.
- The adaptation diagnostic framework can stand alone as a separate assessment effort, or it can be aligned and/or incorporated into other agency activities (more said on this below). Some steps in the framework could provide input into such efforts as transportation planning (for example, identifying vulnerable areas or populations that need to be considered as a metropolitan area develops its improvement program or incorporating climate change–related considerations into project prioritization).
- The lack of engineering-relevant and spatially precise climate data and the uncertainty surrounding those data remain obstacles and will likely remain so for the foreseeable future despite the best efforts of climate modelers. This should not,

however, be an excuse for inaction. Some governments, such as New York City, realize the data shortcomings issue and have put forth alternative approaches (e.g., flexible adaptation pathways) to enable prudent decision making in light of the uncertainty. This was perhaps best expressed in the Australian government's white paper on climate change—"Uncertainty is a reason for flexibility and creativity, not for delay" (Department of Climate Change 2009).

- Climate-related risk to the transportation system is one of the most important concepts in adaptation planning. Risk is broadly defined as relating to impacts beyond simply the failure of an asset. It relates to the failure of that asset in addition to the consequences or magnitudes of costs associated with that failure. In this case, a consequence might be the direct replacement costs of the asset, direct and indirect costs to asset users and, even more broadly, the economic costs to society given the disruption to transportation caused by failure of the asset or even temporary loss of its services (e.g., a road is unusable when it is under water).

8.2.4 Agency Functions

- Climate change adaptation can be incorporated into many functional activities of a transportation agency—planning, environmental analysis, design, infrastructure retrofit, construction, operations, maintenance, emergency response, and public outreach and communications. Each activity will usually require different analysis approaches, data, and resulting strategies.
- It is likely that the operations and maintenance functions of a transportation agency will be the first to experience the impacts of a changing climate on a transportation system, whether this includes responding to system damage and disruption after an extreme weather event or, over the longer term, dealing with the consequences of climate changes (e.g., proliferation of new invasive species, longer mowing seasons, and less snow but more ice on the roads).
- For those transportation agencies that are planning for changes and impacts that will occur due to climate change, an asset management system is well suited to help in such an effort. Given the periodic nature of infrastructure condition monitoring in asset management systems, combined with the maintenance efforts catalogued in maintenance management systems, these existing systems could be an important platform for incorporating climate change considerations into agency decision making.
- Leadership is critical. Strong mandates (legislative or administrative) to consider adaptation and provide relevant data greatly encourage adaptation activities. That said, they need not be a prerequisite. Absent mandates, strong state or local leadership by individuals concerned about climate change can also spur action as is the case in most U.S. examples. Visible, on-the-ground changes, as in Alaska or in the aftermath of strong storms, can also focus attention on the topic.

8.3 Suggested Research

The literature review conducted for this project, the ongoing interaction with adaptation researchers from around the world, and input from the NCHRP Project 20-83(05) panel led to a set of recommended research statements that can help define a research portfolio for advancing the state of the practice and the state of the art in adaptation research. This study identified some of the key adaptation research needs as linked to a project development life cycle. By this is meant the key activities and/or functions that are associated with taking an initial idea or need and turning it into an implemented project that will likely over time experience numerous rehabilitation and reconstruction efforts. So, for example, this report asks, how can adaptation considerations be included in the planning process that precedes project design? How should project designs be undertaken to provide flexibility in the face of uncertainty in future environmental conditions? How should state transportation agencies look at operations and maintenance in light of extreme weather events?

TRB *Special Report 299: A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy* provided some points of departure for the research needs identified in the following paragraphs (Committee for Study on Transportation Research Programs to Address Energy and Climate Change 2009). In addition, the research team attended several international and national conferences on adaptation and has been in contact with other adaptation researchers throughout the world. Although this section does not claim to contain an exhaustive list of research needs, it does represent the current thinking on what research is needed to further adaptation planning in the United States. Note that this section does not describe research that is likely needed in climate science or meteorology. Because much of what transportation engineers and planners will do in adaptation clearly depends on the reliability and credibility of the information provided to them by the climate scientists, such information is a concern. However, to even begin to outline a research agenda for the climate science component of adaptation planning for transportation systems would be well beyond the scope of this study.

8.3.1 Planning

Planning constitutes those activities that lay the groundwork for individual projects, including identifying current problems in the transportation network and anticipating where future problems might occur. Planning is usually data focused and relies on analysis and evaluation processes to identify the most cost-effective set of strategies that will improve transportation system performance.

With respect to planning, several potential research topics deserve attention:

1. **Incorporation of uncertainty into long-range transportation planning:** Most transportation plans have a 25- to 30-year timeframe, although a few MPOs have adopted 40- and 50-year plans. From a methodological and process perspective, how can potential climate change–related stresses be incorporated into the long-range planning process? What type of data is necessary to present credible forecasts that can be used as part of the transportation planning process? How can climate change scenario analyses be integrated into the traditional transportation planning process?
2. **Procedures and tools for identifying vulnerable assets:** Research and studies to date have generally concluded that it is beyond the scope of most planning efforts to assess every single asset in a transportation system for its vulnerability to potential changes in climate and environmental conditions. That instead, the more effective approach is to identify those assets that are the most vulnerable to environmental stressors. Vulnerability could be related to the asset location, hydrologic and soil conditions, and terrain characteristics. For example, an entire section of track might not be vulnerable to flooding, but a short segment over a culvert or bridge might be the weak link in the section. This segment would then become the focus of a more detailed investigation on how to protect this asset at this location. Research is needed on how to best identify vulnerable assets in a state or region that provides the most cost-effective and strategic use of limited planning funds.
3. **Procedures and tools for identifying vulnerable population groups:** As was seen in recent major disasters (e.g., Hurricane Katrina), population groups are often affected differently. Those without cars, for example, are likely to be stranded unless some alterative form of transportation or protected location is provided. Research is needed that links potential climate-related environmental hazards to the location of vulnerable populations. Even more fundamentally, research is needed on how "vulnerable populations" is defined in the context of emergency evacuations or other actions related to extreme weather events.
4. **Procedures and tools for identifying vulnerable network links:** One of the adaptation characteristics inherent in most networks is the ability to restructure flows so as to avoid any particular location where there is a disruption. Network redundancy and the ability of a network to rebound from a disruption (resiliency) is a critical aspect of a state's or region's resilience to natural disasters. Most every system will have critical elements of national significance that, if disrupted, may threaten this resiliency. Identifying the links and nodes with the highest incremental cost would help set adaptation priorities.
5. **Travel demand and mode choice:** More research is needed on the effect of weather and climate on travel demand and mode choice, to separate the effects of number of trips made, mode switching, congestion avoidance, travel timing, and regional climate differences. What are the expected costs associated with weather-related road delays?
6. **Intercity passenger data:** There is a national need for systematically and periodically collecting intercity passenger data, which often do not exist at the state level and lag far behind intra-city transport data in quality and quantity. This research entails not only identifying and developing accurate data, but also strategies for embedding improved information into planning and engineering designs and improved analysis tools, specifically aimed at understanding the implications of climate change on intercity transportation.
7. **Co-benefits of adaptation strategies with other priorities:** With limited resources to both maintain asset conditions as well as increase capacity, most state transportation agencies will find it difficult to implement a state-wide adaptation investment strategy. Thus, it seems likely that one element of a successful strategy will be linking adaptation actions to other investment priorities that are undertaken to achieve other goals. For example, a bridge rehabilitation and/or replacement program could include consideration of different hydrologic conditions in the future. Or land use strategies aimed at increasing densities of new development could do so in areas that are protected from increased chances of flooding.
8. **Visualization tools and techniques for effective public involvement:** The transportation planning process has traditionally been very open to the involvement of public groups and individuals. Over the past decade, greater attention has been given to the methods, tools, and techniques for visualizing the impacts of different investment strategies. What is the best way to convey to the general public the likely positive or negative impacts of different climate futures? Very little research has been conducted on how to best convey climate change–related impacts.

8.3.2 Project Development

Project development includes those steps that take a project from a planning idea to final plans, specifications, and estimates. Thus, for example, any environmental analysis that must be undertaken to satisfy federal or state environmental requirements will occur during the project development stage, as will preliminary and final engineering. Research in the following project development areas deserves attention:

9. **Environmental variable inputs into design:** Improved climate data are needed at many different scales of application, especially downscaled data able to inform decisions on specific bridges, roadways, and other facilities. As noted earlier, the intent of the proposed research portfolio is not to focus so much on climate science research. However, design engineers will need to have better information on likely future environmental conditions if they are to consider such factors in the design process. For example, one possible strategy is to consider revised intensity, duration, and frequency (i-d-f) curves for precipitation and a strategy to modify runoff factors, which are used in the design of drainage systems and stormwater management facilities. Techniques have already been developed to derive future i-d-f curves from global climate models and they are being generated for many areas overseas and especially in Canada. The development of comparable future i-d-f curves in the United States would be of great value to engineers. Pavement engineers would benefit from forecasted temperature ranges to adapt current design procedures to future conditions.
10. **Environmental analysis and climate change factors:** How should climate change impacts be considered in the environmental analysis process? Proposed guidance from the CEQ suggests that at some point in the future environmental analyses required for projects having significant impact on the environment will include consideration of climate change as part of the analyses. What types of approaches can be used to do this? What data will be needed? What tools will be necessary to conduct such an analysis in a credible way? How can the results of the analyses be presented to decision makers in a way that conveys the importance of adaptation strategies?
11. **Design strategies:** Agencies can respond to climate change threats in a variety of ways. For example, strategies could include design for failure (simply replace the asset when it is destroyed or can no longer function), design for obsolescence (use of shorter design lives), design for adaptation, design to avoid, design to protect, or no design at all (i.e., no build). Research should be conducted that looks at the advantages and disadvantages of these different strategies. Under what circumstance would a particular strategy make most sense?
12. **Damage functions and cost estimates:** State DOTs have many years of experience with reacting and responding to extreme weather events. To determine with any certainty what the risk is to certain types of assets, it might be useful to categorize the different types of damage that has been caused by different types of weather events and, for particular types of failures, to determine the range of costs that might be expected. This might require going through records of failure incidents and their costs. This information could be very useful to the conduct of risk analyses, similar to the use of depth–damage functions for assessing flooding risks for various building types. The Gulf Coast 2 project will provide such estimates for the Mobile, Alabama, metropolitan area, but this proposed research would provide a broader perspective on damages and costs.
13. **Adaptive design processes:** Similar to suggestion 11, this project would examine how, for a particular project, adaptive design characteristics could be incorporated into project design. For example, how is project design flexibility provided for in the future when environmental conditions might change? What are examples from other infrastructure areas where adaptive design capacity has been incorporated into project design?
14. **Administrative/procedural/legal barriers to adaptation:** There are numerous examples of administrative/procedural/legal barriers to adopting a more flexible design approach that recognizes the need for adaptive capacity. For example, some state DOT officials have suggested that there are legal issues with increasing culvert size that could lead to downstream flooding liabilities. One state DOT indicated that consideration of adaptive capacity in design concepts has been removed from consideration when the value engineering portion of the project development process looks for ways of reducing costs. This project would examine and categorize systematically the barriers that state DOTs and other transportation agencies might face in implementing an adaptive capacity design approach.
15. **Impacts on natural resource mitigation actions:** Most state DOTs have many years of experience with putting in place mitigation strategies as part of environmental agreements that come out of the project development process. For example, replacement wetlands are very common as part of project environmental agreements intended to mitigate the taking of wetlands for project construction. However, as some state DOTs have noted, these mitigation agreements often require the agencies to manage the resource in perpetuity. The research topic here is to understand the implications of changing climatic conditions to the function of mitigation actions that themselves could be affected by such conditions. Wetlands would be an important focus of such research.
16. **Non-transportation strategies to mitigate hazardous conditions:** Transportation planners and engineers usually focus on transportation strategies when thinking about climate adaptation approaches. In a recent adaptation workshop held at the national AASHTO meeting, the Iowa DOT described how it built structures in a river

with highway dollars to channel flood river flow away from a downstream bridge. This project would examine different non-transportation strategies that could be used to protect transportation assets. In addition, a broader perspective on the benefits of hazard protection would be examined. That is, how can such non-transportation strategies provide the greatest protection not just for transportation assets, but also for communities and other critical infrastructure?

17. **Off-site impacts, adaptation, and mitigation:** Highway projects are not located, designed, and operated in isolation. The environment surrounding the highway system plays an important role in how the system operates and this off-site environment could well be affected by climate change and extreme weather more so than the highway itself. Highway agencies are not likely to build in the resilience to avoid or adapt to the impacts coming from off site. Therefore, the highway agencies must find proactive ways to protect the highway system from off-site threats. An example would be to participate in municipal stormwater management activities to address stormwater impacts upstream of the highway system. This project would identify the many off-site functions and activities that could affect a highway facility, and describe the actions and strategies that highway agencies could take to mitigate the negative impact of such activities.

8.3.3 Construction, Operations, and Maintenance

Weather significantly affects construction activities from high temperatures (hours of labor) and types of construction materials. In addition, one of the earliest manifestations of a changing climate will occur in state DOT operations and maintenance. This manifestation includes such activities as responding to and recovering from extreme weather events and developing different operations and maintenance strategies for routine activities (e.g., longer growing season, more intense snow storms, etc.). The following research topics relating to construction, operations, and maintenance deserve attention:

18. **Construction-related impacts of weather and climate change:** Changing climate and weather conditions could influence construction activities in a variety of ways. In a positive way, warmer temperatures throughout the year will lengthen the construction season in states that usually curtail activities during the winter months. However, more extreme temperatures during the summer months could have negative impacts on hours of construction during mid-summer. With respect to precipitation, more intense storms could cause more erosion from construction sites and thus require greater mitigation. This project would examine the range of impacts that different climate stressors might have on construction, ranging from the physical activities involved with completing a project to the use of labor on site.
19. **New and weather-resistant materials and sensors for project construction:** Temperature change affects in some way every component of infrastructure design because the materials used in building a structure will usually exhibit some contraction and expansion varying with the temperature. The effect of changing levels of precipitation would most affect foundation and pavement design, especially if precipitation levels increase significantly over today's levels. More moisture in the soil and the hydrostatic pressure build-up behind such structures as retaining walls and abutments might cause a rethinking of the types of materials used in construction and in dimensions such as slab thickness. Increasing storm strengths will likely be accompanied by increasing and sustained wind speeds. Greater wind speeds could require a rethinking of the support structures for traffic signs and signals. It seems likely that the advances in material sciences (with special application of nano-technologies), sensors, computer processing, and communications abilities could also have a significant impact on the way infrastructure is designed. Sensors that monitor changing pressures on a building or bridge and thus issue a warning when pressures become abnormal are already available and in limited use. "Smart" infrastructure can be envisioned that directs highly turbulent and fast water flows away from bridge columns and thus reduce the potential for bridge scour. Sensors could be embedded in pavements and bridge decks that monitor the changing stress and strain as temperatures change, allowing remedial action to be taken before complete failure occurs. Similar sensors could be applied to bridge structures in high-wind conditions to change material properties that allow the bridge to survive abnormal wind speeds.

    This project would examine the most challenging climate stressors from the perspective of materials strength and durability. It would describe the ranges in which materials can be used without concern for failure but identify those conditions (such as prolonged heat) in which strength and durability might lessen. The project would outline specific research that would be needed to ensure that the construction materials used for long-lived transportation projects will withstand possible future conditions. In addition, it would identify promising "smart" technologies that could be integrated into project design to account for weather-related factors.

20. **Response strategies for extreme weather events:** Data on extreme weather events suggest that the last several decades have seen an increase over historical patterns of such events. State DOTs have learned how to respond to such extreme events, but with the frequency and intensity of these events likely to increase, state officials need to examine how transportation agencies should prepare and respond to these changing conditions. For example, some states are pre-positioning building materials that might be necessary in the event of bridge or culvert collapses. The recent experience in Vermont with Tropical Storm Irene showed the value of having regional traffic management control centers that could direct the response and recovery activities of transportation organizations. This project would examine the different strategies states are currently adopting as well as identify others that could be undertaken.
21. **Operations and maintenance activities as an early warning system:** Many of the climate adaptation frameworks that have been created to guide adaptation planning use threshold criteria to indicate when environmental conditions have reached a point where climate-related change is now sufficiently established that thought needs to be given to how state DOT activities might have to change. This project would examine how routine operations and maintenance activities could be used to provide the means by which such threshold conditions could be monitored and acted upon when reached. For example, if rock/mudslides or road flooding have reached an occurrence rate much higher than historical records, what should the state DOT do differently in the future to protect against such events?
22. **Institutional and procedural barriers to operations and maintenance strategies aimed at extreme weather events:** Many rules and regulations bind what a state DOT can do with respect to operations and maintenance strategies. For example, it has been indicated that some DOTs were prohibited from removing debris from under bridges because they were unable to secure permits to remove it. The presence of the debris clearly raised the vulnerability of the bridge to flood waters. Exploring different operations and maintenance practices and environmental/institutional agreements that limit an agency's ability to reduce risks would be an important research topic.
23. **Emergency management procedures and actions:** In the event of a weather-related disaster, numerous federal and state agencies become involved in providing resources for response and recovery. At the recent AASHTO workshop mentioned earlier, several states recommended that research be undertaken on how the multiagency emergency response activity can be better streamlined and coordinated. For example, one state DOT has automated the federal emergency aid submittal process such that the effort at obtaining federal emergency funding can happen much faster than before. This project would identify actions that could be taken to make emergency management procedures more efficient and effective.

8.3.4 System Management and Monitoring

Ongoing management of the transportation system asset base is one of the most important functions of a state transportation agency. In the context of climate change, this would entail monitoring environmental conditions for any changes in environmental stresses that might result in system disruption. As noted above, this can be tied into threshold criteria where once a certain threshold is reached, additional actions might be necessary. Research in the following system management and monitoring areas deserve attention:

24. **Use of asset management systems:** Performance-based asset management is a concept that is being encouraged as part of any transportation investment program, especially those supported by federal dollars (stewardship of taxpayer investment). Not only is such a concept valuable in identifying the best investment opportunities in a normal investment environment, but they can become even more valuable for monitoring performance and condition over time. The inventory data exists in asset management systems to allow state officials to flag those assets that need to be watched carefully in terms of vulnerability to changing environmental conditions. This research would examine how asset management systems could be used as part of a climate change–oriented system management strategy.
25. **Development of asset/maintenance management systems for culverts:** Recent experience with extreme weather events has indicated that culverts are one of the most vulnerable components of the road network. This vulnerability has been shown to be due to not only inadequate design of the culverts themselves but also, more importantly, inadequate maintenance of the culverts. A large number of road washouts from Tropical Storm Irene in Vermont were caused by culverts that were clogged and had reduced capacity due to debris that had lodged in the culvert itself. This research would examine best practices of culvert asset management (only a few have been identified) and propose strategies for developing a culvert maintenance and design strategy for expected future extreme weather events.

8.3.5 Other

Research into the following areas would also be beneficial:

26. **Institutional Change and Capacity Building:** In many ways, considering adaptation within the planning and project development context requires a very different approach to project development than what has been done previously. This might require new organizational structures for dealing with climate/weather-related events and new skills and tools. In other words, transportation agencies will need opportunities for building capacity and examples of how to change institutional structures to expedite adaptation and mitigation strategies. This project would recommend capacity-building initiatives and conduct research on institutional barriers to adaptive management practices and recommended solutions.
27. **Clearinghouse:** For transportation practitioners, a clearinghouse of best practices in adaptive management strategies would provide an important resource for exchanging information as more is learned about adaptive climate change strategies. This should include highlighting a wide range of climate change adaptation strategies and in particular fostering an exchange of information on approaches for preparing for, responding to, and recovering from extreme weather events.

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APPENDIX A

Climate Change Modeling Platform Used for This Research

The projections of temperature and precipitation changes in this research were developed using a tool called "MAGICC/SCENGEN" (M/S; Wigley 2008). This tool contains parameterized outputs from 20 general circulation models (GCMs). In this research, 10 models were used, which gave a wide range of projected changes in climate, particularly at the regional scale. The GCMs were the Canadian Centre for Climate Modeling CGCM3, the National Center for Atmospheric Research CCSM3, the Geophysical Fluid Dynamics Laboratory GFDL CM2.0 and CM2.1 (two different models), Institute Pierre Simon Laplace (France) IPSL_CM4, Center for Climate System Research (Japan) MIROC 3.2 (medium resolution), Max Planck Institute for Meteorology (Germany) ECHAM5/MPI-OM, Meteorological Research Institute (Japan) MRI-CGCM 2.3.2, Hadley Centre for Climate Prediction and Research (United Kingdom) HadCM3 and HadGEM1. These models were selected in consultation with Dr. Tom Wigley of the National Center for Atmospheric Research, the developer of M/S. He found that these 10 models best simulate the current climate of North America. While a model's ability to simulate current climate with fewer errors than other models does not necessarily mean that model will more reliably simulate future conditions, it does provide more faith in a model's capabilities.

Changes in temperature and precipitation are based on M/S's estimation of climate in 2050 compared to the model's estimation of climate in 2010; these changes are not compared to observed conditions.

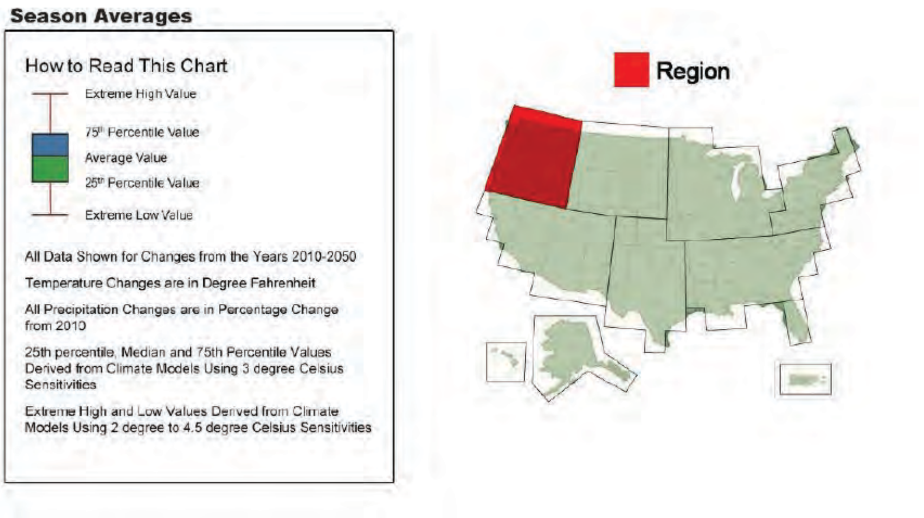
M/S is a combination of two models: MAGICC and SCENGEN. MAGICC calculates change in global mean temperature and sea-level rise. Users can select various factors such as greenhouse gas (GHG) emissions scenarios and climate sensitivity. The latter is how much global average temperatures are projected to rise with a doubling of carbon dioxide levels in the atmosphere. SCENGEN divides the world into 5-degree by 5-degree grid boxes. One degree is about 60 miles long in the mid-latitudes, so each grid box is approximately 300 miles across. For each GCM, SCENGEN calculates how temperature and precipitation change for each degree of change in *mean global temperature.* A user can select an emissions scenario and climate sensitivity for MAGICC, which gives an estimate of change in global mean temperature. For SCENGEN, the user can select all or some of the GCMs in the model, as well as a region of the world, and the time frame into the future for the climate projections (e.g., 2050, 2100). M/S will give regional temperature and precipitation projections for each model and will also calculate average changes across all the selected models.

The parameterization scheme in M/S can also lead to a very wide range in temperature and, particularly, precipitation projections at the regional scale. The scaling of regional temperature and precipitation to global mean temperature can lead to very significant changes when there are large changes in global mean temperature. This happens, for example, when the high GHG emissions scenario A1FI is used and a high climate sensitivity such as 4.5°C is assumed.

The results presented in this report are for all 10 of the GCMs using the A1FI emissions scenario. The "model average" is the average of all 10 models. The "median" is the mean of the 5th and 6th GCMs (by rank). The 25th and 75th percentile changes are, respectively, between the 3rd and 4th and 7th and 8th GCMs by rank.

APPENDIX B

Projected Climate Changes by Region



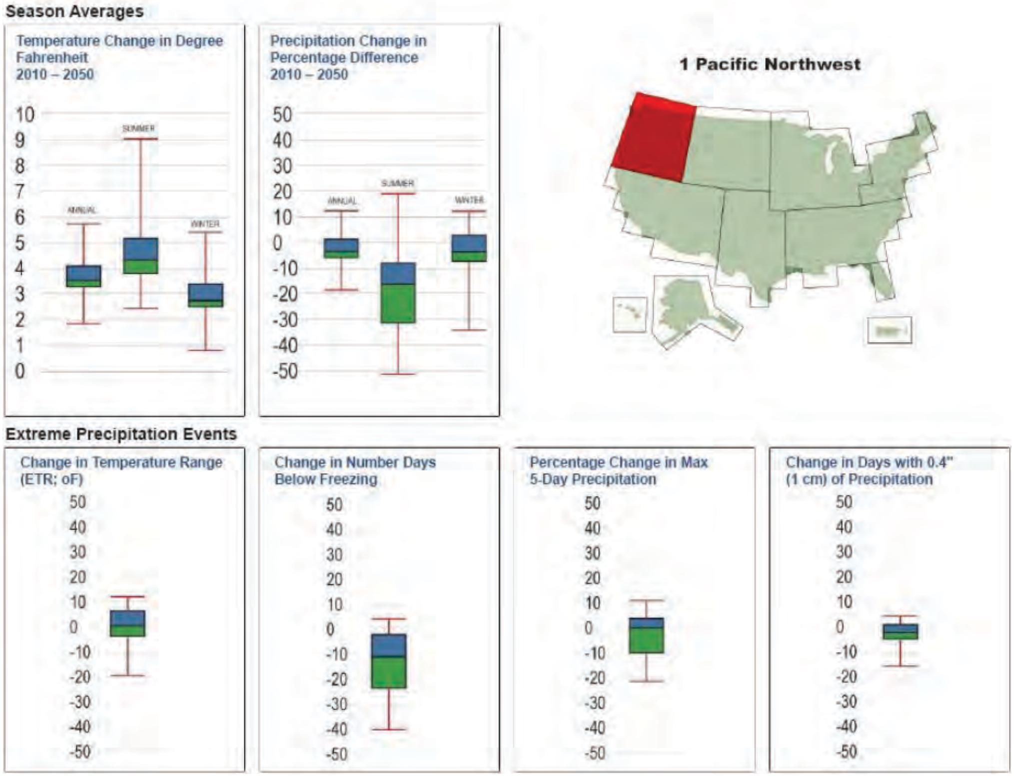
All Data Shown for Changes from the Years 2010-2050

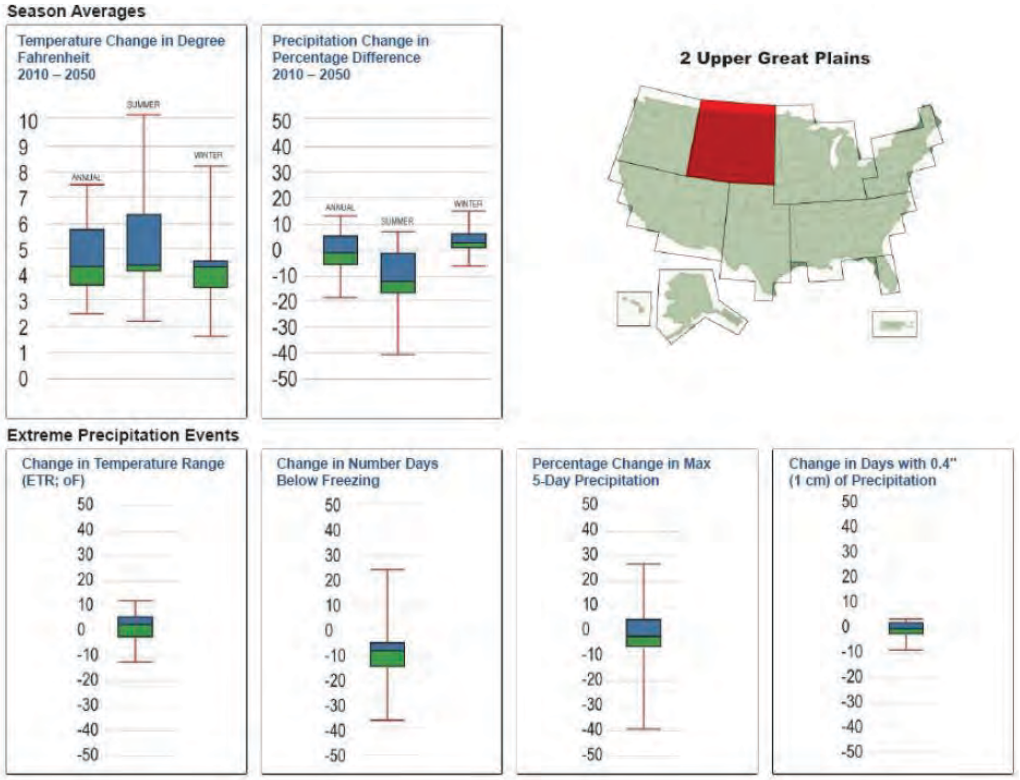
Temperature Changes are in Degree Fahrenheit

All Precipitation Changes are in Percentage Change from 2010

25th percentile, Median and 75th Percentile Values Derived from Climate Models Using 3 degree Celsius Sensitivities

Extreme High and Low Values Derived from Climate Models Using 2 degree to 4.5 degree Celsius Sensitivities




Season Averages
Temperature Change in Degree Fahrenheit 2010 – 2050
10
9
8
7
6
5
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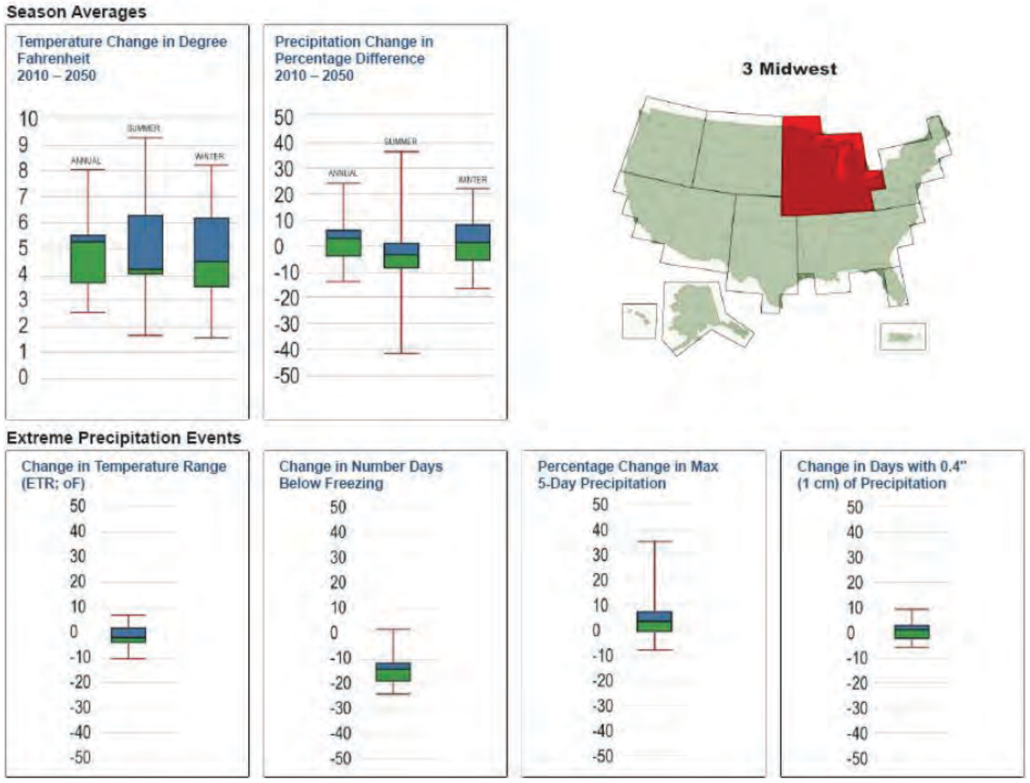
2
1
0
ANNUAL
SUMMER
WINTER
Precipitation Change in Percentage Difference 2010 – 2050
50
40
30
20
10
0
-10
-20
-30
-40
-50
ANNUAL
SUMMER
WINTER
2 Upper Great Plains
Extreme Precipitation Events
Change in Temperature Range (ETR; oF)
Change in Number Days Below Freezing
Percentage Change in Max 5-Day Precipitation
Change in Days with 0.4" (1 cm) of Precipitation
50
40
30
20
10
0
-10
-20
-30
-40
-50


Season Averages
Temperature Change in Degree Fahrenheit 2010 – 2050
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SUMMER
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Precipitation Change in Percentage Difference 2010 – 2050
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-10
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-40
-50
ANNUAL
SUMMER
WINTER
3 Midwest
Extreme Precipitation Events
Change in Temperature Range (ETR; oF)
Change in Number Days Below Freezing
Percentage Change in Max 5-Day Precipitation
Change in Days with 0.4" (1 cm) of Precipitation
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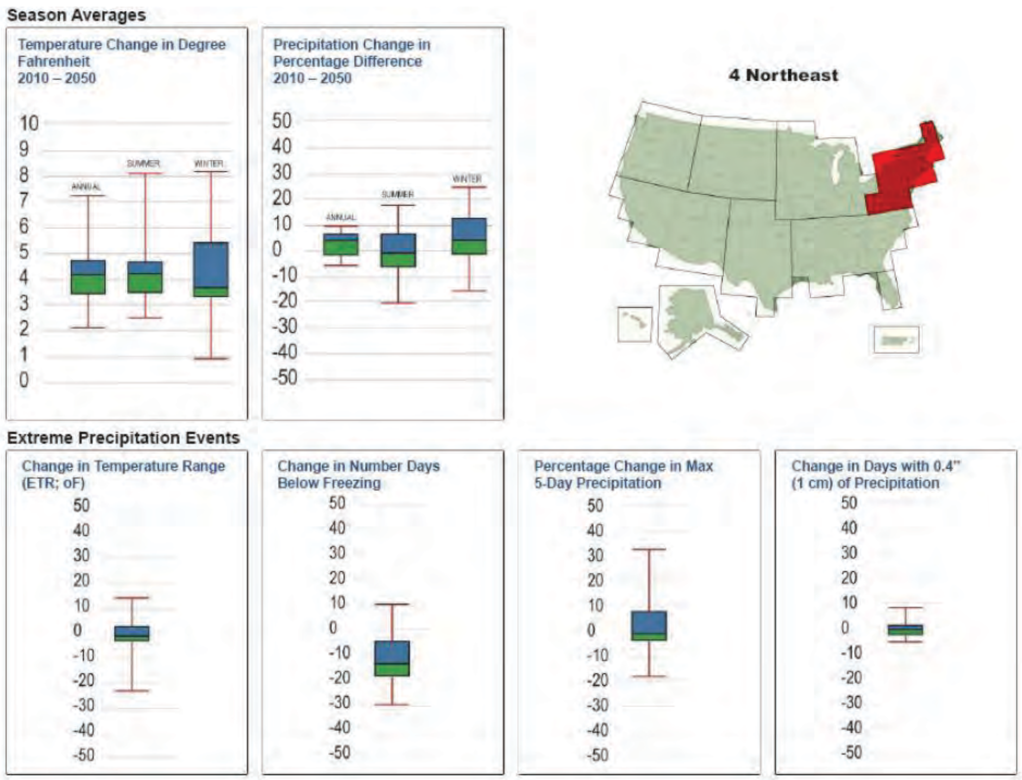
Season Averages
Temperature Change in Degree Fahrenheit 2010 – 2050
10 9 8 7 6 5 4 3 2 1 0
ANNUAL
SUMMER
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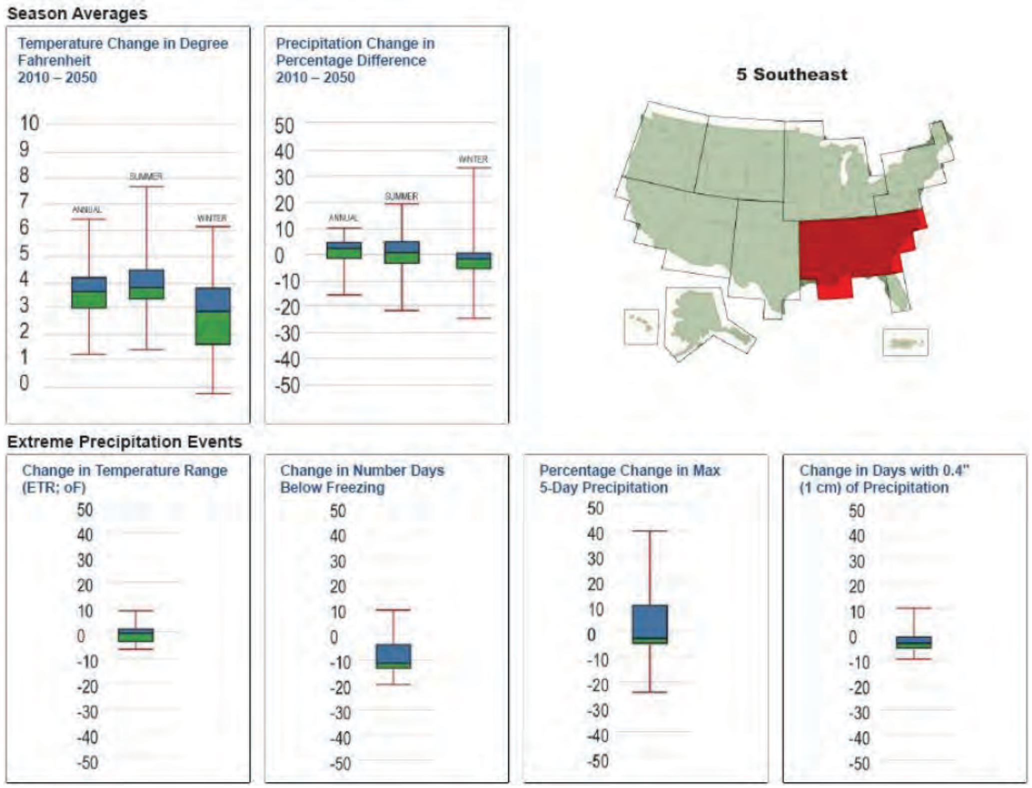
Precipitation Change in Percentage Difference 2010 – 2050
50 40 30 20 10 0 -10 -20 -30 -40 -50
ANNUAL
SUMMER
WINTER
4 Northeast
Extreme Precipitation Events
Change in Temperature Range (ETR; oF)
Change in Number Days Below Freezing
Percentage Change in Max 5-Day Precipitation
Change in Days with 0.4" (1 cm) of Precipitation
50 40 30 20 10 0 -10 -20 -30 -40 -50


Season Averages
Temperature Change in Degree Fahrenheit 2010 – 2050
10 9 8 7 6 5 4 3 2 1 0
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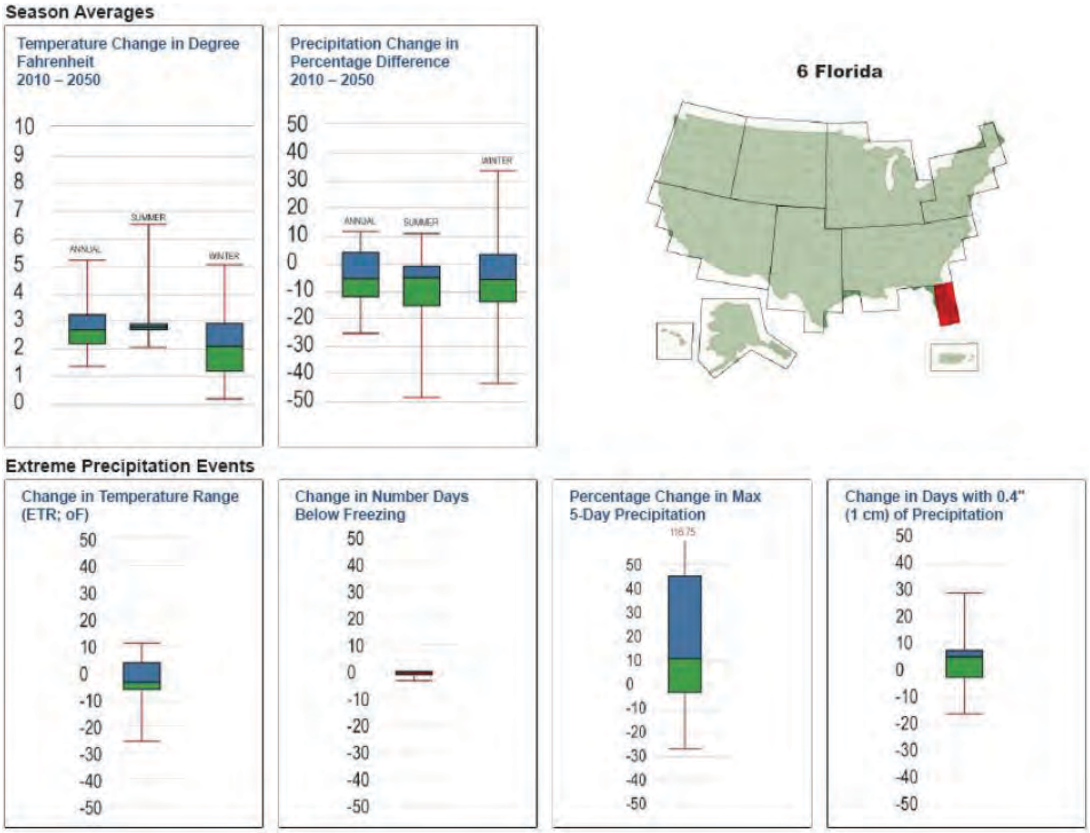
SUMMER
WINTER
Precipitation Change in Percentage Difference 2010 – 2050
50 40 30 20 10 0 -10 -20 -30 -40 -50
ANNUAL
SUMMER
WINTER
5 Southeast
Extreme Precipitation Events
Change in Temperature Range (ETR; oF)
Change in Number Days Below Freezing
Percentage Change in Max 5-Day Precipitation
Change in Days with 0.4" (1 cm) of Precipitation
50 40 30 20 10 0 -10 -20 -30 -40 -50


Season Averages
Temperature Change in Degree Fahrenheit 2010 – 2050
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Precipitation Change in Percentage Difference 2010 – 2050
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ANNUAL
SUMMER
WINTER
6 Florida
Extreme Precipitation Events
Change in Temperature Range (ETR; oF)
Change in Number Days Below Freezing
Percentage Change in Max 5-Day Precipitation
118.75
Change in Days with 0.4" (1 cm) of Precipitation
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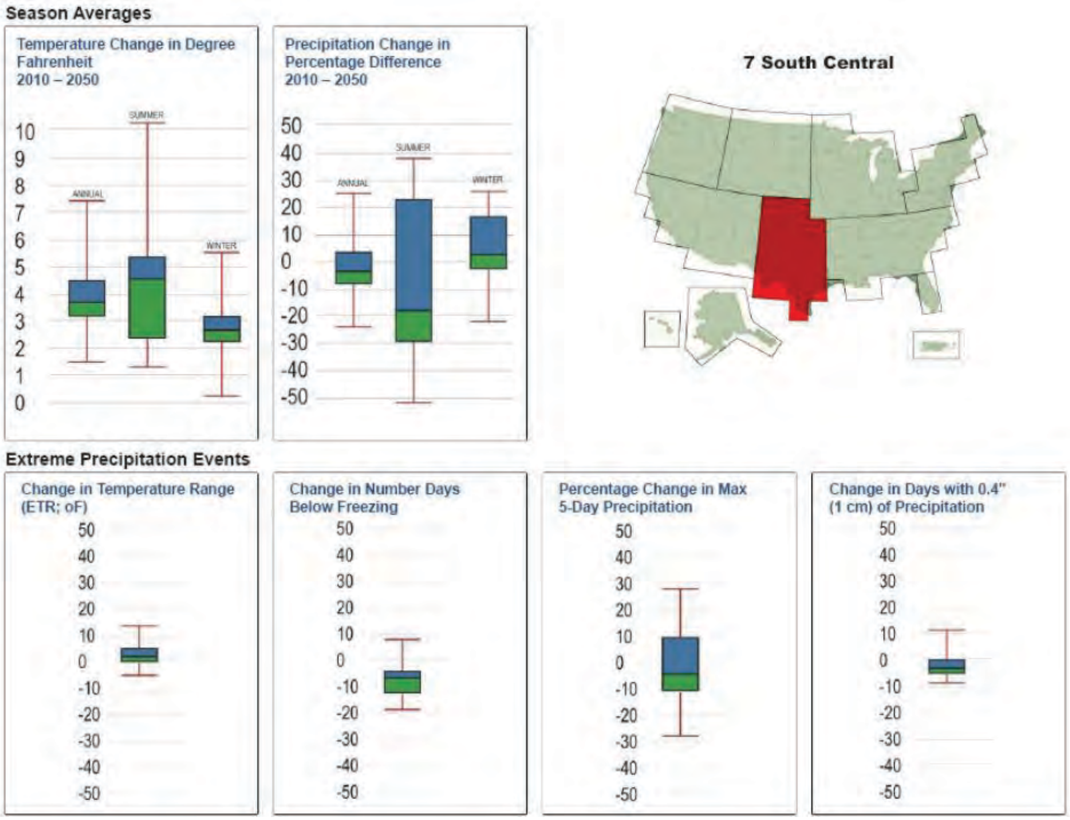
Season Averages
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Precipitation Change in Percentage Difference 2010 – 2050
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ANNUAL
SUMMER
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7 South Central
Extreme Precipitation Events
Change in Temperature Range (ETR; oF)
Change in Number Days Below Freezing
Percentage Change in Max 5-Day Precipitation
Change in Days with 0.4" (1 cm) of Precipitation
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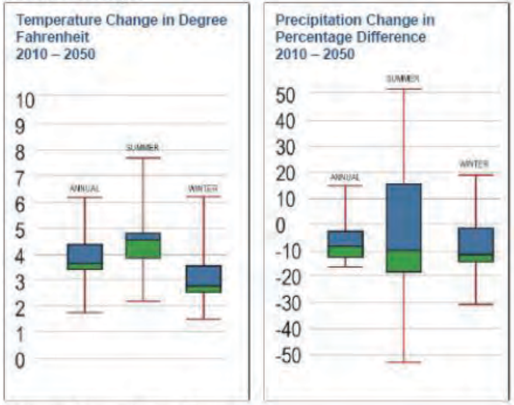
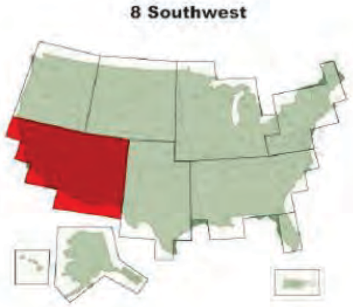
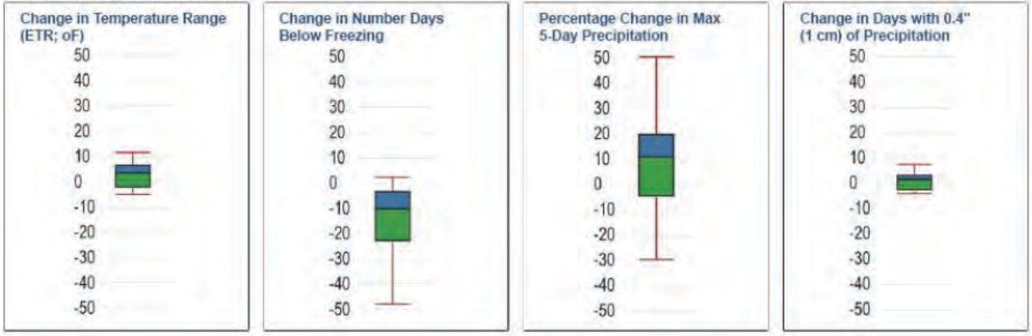
Season Averages

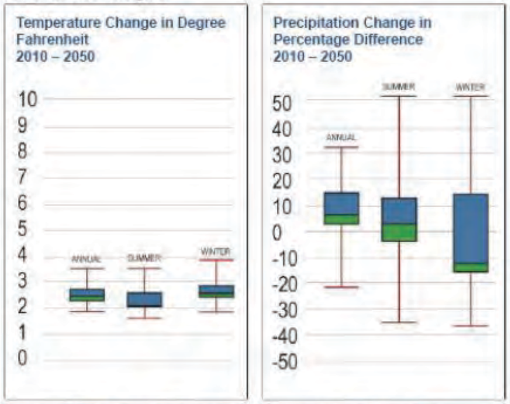


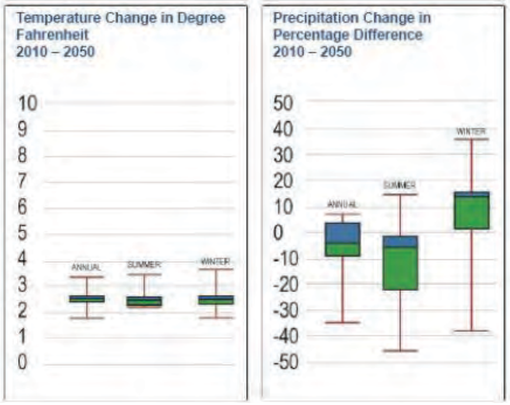


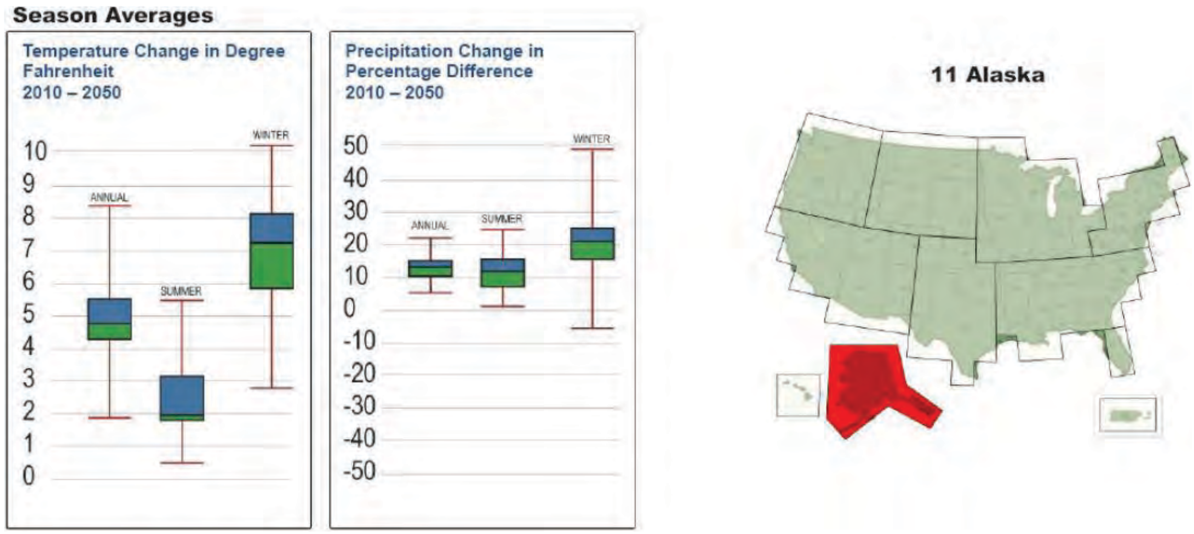
Extreme Precipitation Events



Season Averages






Season Averages
Temperature Change in Degree Fahrenheit 2010 – 2050
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WINTER
Precipitation Change in Percentage Difference 2010 – 2050
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ANNUAL
SUMMER
WINTER
11 Alaska

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation