National Cooperative Highway Research Program

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

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Glossary

Adaptation - Actions taken to reduce the vulnerability of natural and human systems or increase system resiliency in light of expected climate change.

Adaptive capacity- The ability of a system to adjust to climate change (including climate variability and extremes) so as to moderate potential damages, take advantage of opportunities, or cope with the consequences.

Adaptive management - An approach to adaptation decision-making that, recognizing climate projection uncertainty, promotes the preservation of flexibility in responding to a wide range of possible climate futures. The most appropriate adaptation strategy can then be employed as climate trajectories become clearer over time. Adaptive management aims to avoid present-day decisions that can result in maladaptations or those that preclude or add expense to adaptation actions later on.

Anthropogenic emissions - Emissions of greenhouse gases and aerosols associated with human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock, fertilization, etc.

Council on Environmental Quality (CEQ) - Coordinates federal environmental efforts and works closely with agencies and other White House offices in the development of environmental policies and initiatives. The CEQ was established within the Executive Office of the President by Congress as part of the National Environmental Policy Act of 1969 (NEPA) and additional responsibilities were provided by the Environmental Quality Improvement Act of 1970.

Climate extremes - Climate or weather events that occur infrequently (i.e. have long recurrence intervals)

Climate projection - The modeled response of the climate system to a given atmospheric concentration of greenhouse gases and aerosols.

Climate stressors - Climate or weather-related events that pose a threat to transportation infrastructure

Co-benefits – Benefits from adaptation actions other than those gained from reducing climate risks.

Downscaling – An estimate of climate conditions at higher spatial resolution than is produced by GCMs. 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. Assuming the relationship is unchanged, one can determine the present-day relationship and use it to estimate how future climate at a specific location will change.

Emissions scenario - An estimate of the GHG and aerosol emissions associated with a chosen trajectory of global population growth, economic activity, trade, and technological change. Emissions scenarios are inputs to the general circulation models used in the development of climate projections.

Eustatic sea level rise - A change in global average sea level brought about by an increase in the volume of the world oceans due to the melting of ice sheets and glaciers and the thermal expansion of ocean waters.

Evapotranspiration - The process by which water re-enters the atmosphere through evaporation from the ground and transpiration by plants.

Extreme weather events - Weather that includes intensities that are historically seen very rarely. For example, consecutive days above 100 degrees temperature, 500-year storms, etc.

General circulation model (GCM) - Models used to simulate the atmospheric, oceanic, and land processes (and their interrelationships) that affect climate across the globe.

Greenhouse gases (GHG) - Atmospheric gases such as carbon dioxide, methane, nitrous oxide, ozone, and water vapor that absorb infrared radiation from the sun and leading to the warming of the Earth.

Intergovernmental Panel on Climate Change (IPCC) – The IPCC is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts.

Maladaptation - An adaptation action that was either not needed or inappropriately designed for the climate conditions that actually occurred.

Mitigation - Activities aimed at reducing atmospheric GHG concentrations in order to limit the amount of future climate change.

National Climate Assessment (NCA) – The NCA is a report produced every four years for the President and the Congress that integrates, evaluates and interprets the findings of the U.S. Global Change Research Program. NCA assessments act as status reports about climate change science and impacts. NCAs are based on observations made across the country and comparisons of these observations with predictions from climate models. The NCA incorporates advances in climate science into larger social, ecological, and policy systems, and provides integrated analyses of impacts and vulnerability.

Redundancy - The strategic duplication of critical components or functions of a system such that if some components fail the overall system can continue to function

Regional climate model (RCM) – High-resolution models used to simulate the interaction between global climate change and regional/local climate drivers. RCMs incorporate lower-resolution global climate model outputs and adjust them based on the atmospheric, oceanic, and land processes (and their interrelationships) that affect climate at the regional scale. RCMs, for example, more faithfully capture the impacts of local climate drivers like elevation differences and proximity to water bodies.

Relative sea level rise - The sea level rise actually experienced at any given coastal location. Relative sea level rise is determined by a combination of eustatic sea level rise, ocean currents, and the magnitude of land subsidence or uplift.

Resilience –The ability of a system or asset to withstand or recover from the impact of a climate stressor or extreme weather event

Risk – A measure of an asset's climate vulnerability; the threat posed by climate change to a system or asset. Risk is defined as the combination of (1) the likelihood a climate change/weather event will occur and impact the system or asset and (2) the consequence of that impact (in terms of repair costs, user costs/impacts, etc.). Higher likelihood and higher consequence events are given higher risks.

Risk management - The identification, assessment, and prioritization of activities to minimize risks.

Storm surge - An abnormal rise in sea level accompanying a hurricane or other intense storm.

Subsidence - Sinking of the land surface due to natural compaction of sediments or from underground excavation (such as the removal of groundwater or other natural resources).

Surface runoff - During a precipitation event, water that travels over the soil surface to the nearest surface stream and does not infiltrate into the soil.

Sustainable development - Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Thermal expansion - The increase in water volume resulting from the warming of water. The higher water volumes associated with warmer ocean waters are a key contributor to projections of higher sea levels.

Vulnerability - An assessment of a transportation asset that, when exposed to a climate stressor, might result in asset failure or damage that reduces the asset's ability to function as designed.

Executive Summary

Extreme weather events, hurricanes, tropical storms, prolonged intense temperatures, have heightened awareness of a changing climate. Even if one is 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 one can adapt assets and activities to provide transportation system resiliency in the face of changing environmental conditions.

The *Guide* has adopted the following definition of adaptation:

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

The *Guide* is organized to provide important understandings on 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 one can incorporate adaptation concerns into a typical transportation planning process is also described.

The eight-step diagnostic framework includes:

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, 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:

- 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. We do not know 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 we cannot 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 five day) are projected to increase almost everywhere, although the largest increases tend to happen in more northern latitudes.
- Recent research has suggested that we could see fewer hurricanes, but the ones we do see, 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 in to 2 ft (0.2 to 0.6 m) 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 ft (1.5 to 2 m) 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, one could use historical climate information averaged over recent decades. To get estimates of how climate more than two to three decades from now may change, one should use climate models.
- Beyond 2050, it may be prudent to use more than one emissions scenario if you are able to do so. An important reason for using a wide range of emissions scenarios is to find out how your system could be affected by different magnitudes of climate change.
- Climate models project future climate on a sub-daily basis. Using such data, even daily data, is very complicated. To make things much easier, what is typically done is to use average monthly changes in variables such as temperature and precipitation from the 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 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 ES-1, and in addition presents different strategies that can be used to minimize or avoid climate change related disruptions.

Table ES-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 blow-outs; • 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; • Structures will freeze later and thaw earlier with shorter freeze season lengths • Increased freeze-thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces; • Permafrost thawing leads to increased slope instability, landslides and shoreline erosion 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, 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.

	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 at risk of subsidence/heave; • Drought-caused shrinkage of subsurface soils	• 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); • Closure of roadways and underground tunnels 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, tall structures at risk from increased wind speeds	• The number of road closures due to flooding and washouts will likely rise; • Erosion at road construction project sites as heavy rain events take place more frequently; • Road construction activities could be disrupted; • Increase in weather-related highway accidents, delays, and traffic disruptions; • increase in landslides, closures or major disruptions of roads, emergency evacuations and travel delays; • 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

	Climatic/ Weather Change	*Impact to Infrastructure*	*Impact to Operations/ Maintenance*
Sea level rise	**Sea level rise**	• Higher sea levels and storm surges will erode coastal road base and undermine bridge supports; • 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); • Loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action	• Coastal road flooding and damage resulting from sea-level rise and storm surge; • Underground tunnels and other low-lying infrastructure will experience more frequent and severe flooding;
Hurricanes	**Increased hurricane intensity**	• Stronger hurricanes with more precipitation, higher wind speeds, and higher storm surge and waves are projected to increase; • 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

An asset is **vulnerable** to climatic conditions if conditions such as intense precipitation and extreme temperatures and their aftermath (such as a flood exceeding a certain stages and consecutive days of higher than 100^o temperatures) results in asset failure or sufficient damage to reduce its functionality. 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) that asset failure.

The complete risk equation is thus:

Risk = Probability of Climate Event Occurrence x Probability of Asset Failure x Consequence or Costs

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, "piggy backs" adaptation strategies on top of other program functions (e.g., maintenance, rehabilitation, reconstruction, etc.).

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 your 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 potential 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, storm water 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:

- 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 object 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:

- 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 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 over committed 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 would not take significant resources 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.

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 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. 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 one can adapt assets and activities 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 US, 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 document is intended to help transportation professionals identify how their work could be impacted by the consideration of climate change and extreme weather events, and 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 document. Before getting into these details, however, it is important to understand what is meant by the word "adaptation."

What is Adaptation?

A number of organizations have sought to define the concept of adaptation. For purposes of this *Guide*, adaptation is defined as:

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

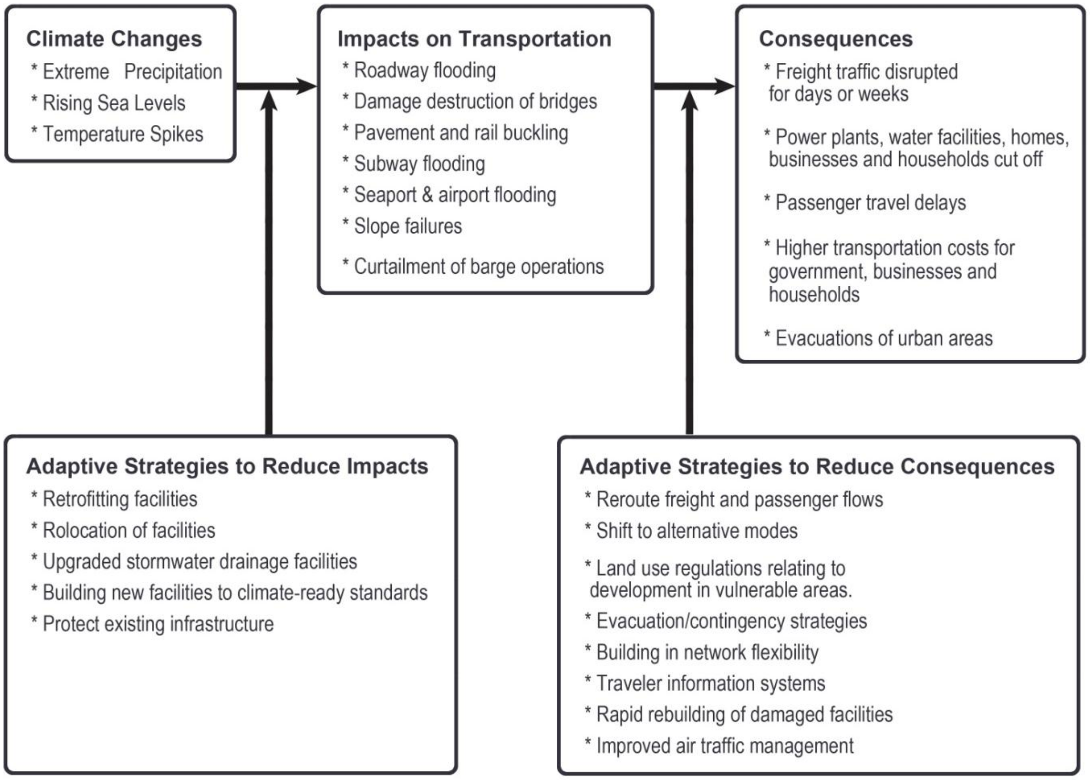
Several aspects of this definition merit attention. First, the types of actions that can be taken to reduce vulnerability to changing environmental conditions could include **avoiding, withstanding,** and/or **taking advantage of** climate variability and impacts. Thus, for roads and other transportation 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 adaptation 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 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 one is preserving the functionality of that asset in future years when more extreme weather events could create a threat. The second type of adaptation strategies 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 (NCA) working group on climate-related transportation impacts, May, 2012. Printed with permission.

Figure 1: Adaptation Strategies and Their Role in Reducing Impacts and the Consequences of Impacts

Who Should Read What?

This *Guide* is organized to allow users 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 might not be that useful (although this section 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.

- 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 section 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 section also provides sources of data and information on climate change that the 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 risk to infrastructure of changing climatic conditions and extreme weather events, one of the key challenges in adaptation planning. This has been repeatedly pointed to 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 user 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 B presents a benefit/cost methodology that can be used for identifying the most beneficial (from a monetary perspective) adaptation alternative.

2. Framework for Adaptation Planning and Strategy Identification

Introduction

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 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 one approaches adaptation strategies from the perspective of reconstructing/rehabilitating existing infrastructure might be different from the consideration of 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; Holper et al 2007; Nobe et al. 2005; Norwell 2004; NRCAN 2011; PIEV and Engineers Canada 2008, 2009; Scotland Ministry of Transport 2011; Swedish Commission on Climate and Vulnerability 2007). Also, several agencies in the U.S. 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-Brinkerhoff 2011; Major and O'Grady 2010; Maurer et al 2011; Nguyn et al 2011; NJTPA. 2011; Sonover et al 2007; SSFM International 2011; and Virginia Department of Transportation 2011).

What are the Steps for Adaptation Planning?

Figure 2 shows a diagnostic framework whose focus is 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 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, one should establish the goals for the analysis and what types of assets will receive attention. In some cases, for example, transportation agencies might focus their attention only on those assets where prior experience with extreme weather suggests future problems will exist; or they might focus on assets that are critical to network performance (e.g., a major bridge crossing), regardless of past experience at that location. It is important to establish this study focus early in the process.

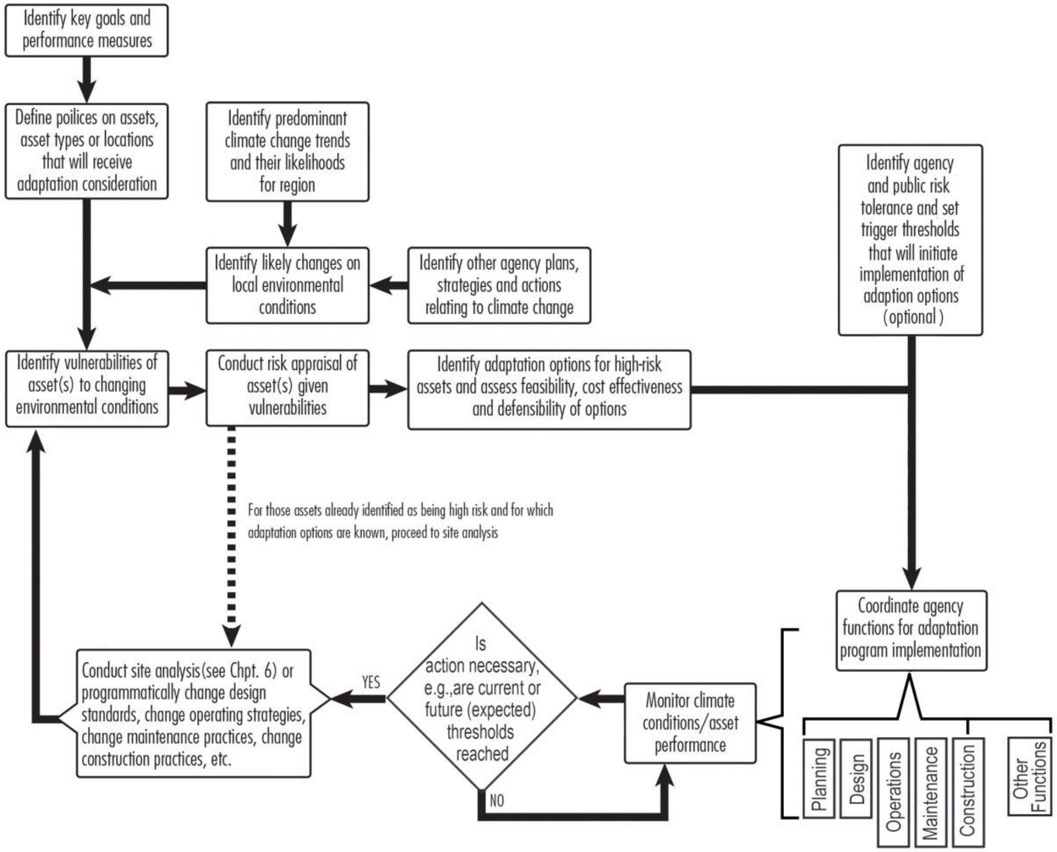


Figure 2: Adaptation Diagnostic Framework

The framework then determines the likely future climatic and weather conditions. In other words, if you are developing strategies to protect assets from higher-than-normal environmental stresses, you have to have 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, one can now determine how vulnerable these assets are to the stresses that will be placed on them. For example, are critical bridges designed to withstand much higher flood flows? Are culverts on key roads likely to handle some percent 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. As compared to another bridge with a higher probability of failure, but if failure does occur, alternative travel routes minimize the disruption to travelers and to the surrounding communities. This bridge 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 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 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 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.

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 which part of the world or United States you are in. 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 managers 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 both 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, 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 IPCC Assessment Report. These global climate change projections were regionally downscaled (both statistically and dynamically, see Chapter 3). The projections were based on relatively moderate and low scenarios of greenhouse gas emissions during the century. The study concluded that combined increases in precipitation, increased storms, less snow pack and more run off 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 sea level rise 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: Identify 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 would 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 different components of an 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 (GCMs) 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:

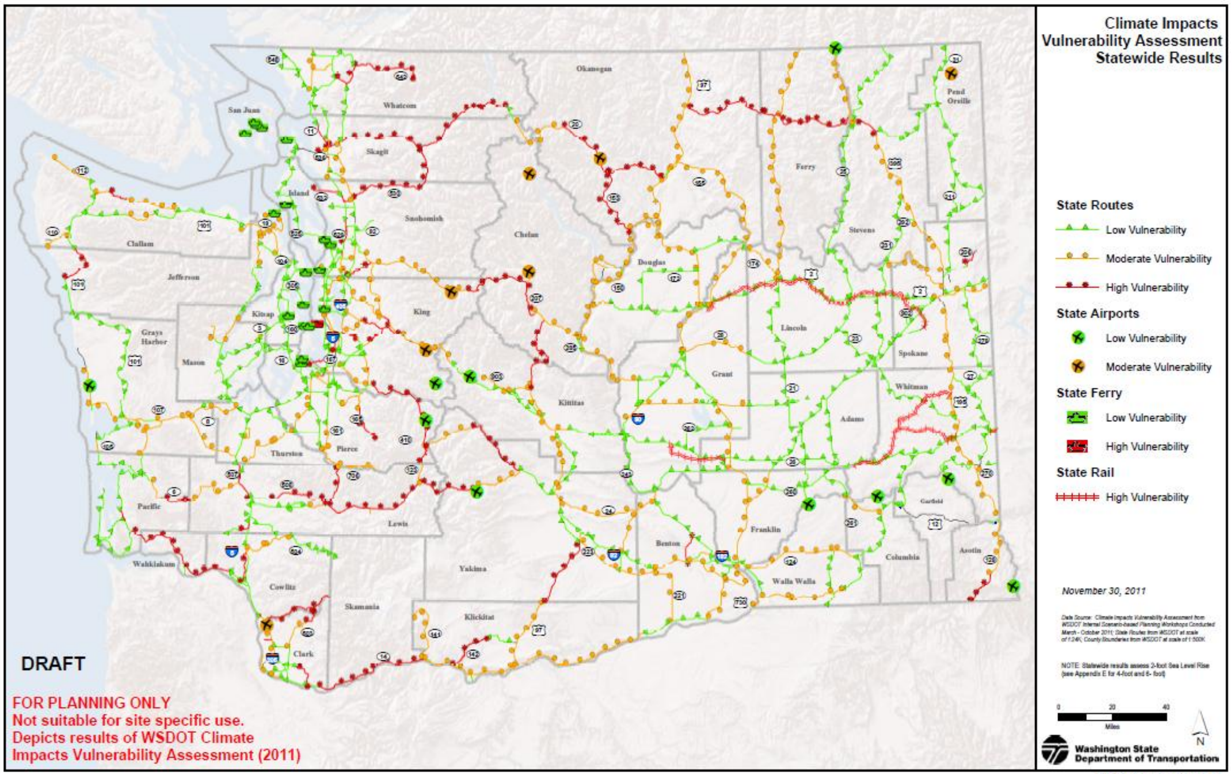
- Change in average precipitation from November through April, currently the months during which snow falls and can accumulate. Total precipitation over this period is an indicator of the size of the snowpack.
- Change in average March and April precipitation, the two months that are important for determining 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 three-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 risk to coastal flooding, including risks to its transportation infrastructure. The risk 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 3 shows the results of a transportation vulnerability assessment for Washington State.

Note in the diagnostic framework (Figure 2) that there is the possibility of proceeding directly to the identification of design or other solutions right after the vulnerability identification and the risk assessment steps. This relates back to step 2 where the agency has established policies on what asset, asset types or locations that will receive attention. However, the agency should proceed with caution in jumping right into adaptation actions. One wants to avoid applying adaptation actions 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 (2008), for example, developed a risk appraisal process based on the following four elements:



Source:http://www.wsdot.wa.gov/NR/rdonlyres/73ADB679-BDA6-4947-93CA-87C157862DD7/0/WSDOT_Project_GHG_Guidance_March_2012.pdf

Figure 3: Climate Change-related Vulnerability in Washington State

> “*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 you lose; 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 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 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 inter-agency 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 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” for agency officials to examine alternative ways of designing, constructing, operating and maintaining transportation infrastructure in light of 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 have now 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. This is done through monitoring of the external conditions and of asset performance/condition either in an asset management system or through some other means.

Step 8: Conduct site analysis or modify design standards (using engineering judgment), operating strategies, maintenance strategies, construction practices, etc.

Once a decision is made to take action, the agency should implement whatever cost effective strategies that seem most appropriate. As shown in Figure 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, WA’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 storm water 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 failures 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; and
- 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 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.

What is the Relationship Between Climate Change and Transportation Planning?

The diagnostic framework shown in Figure 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 in doing 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.

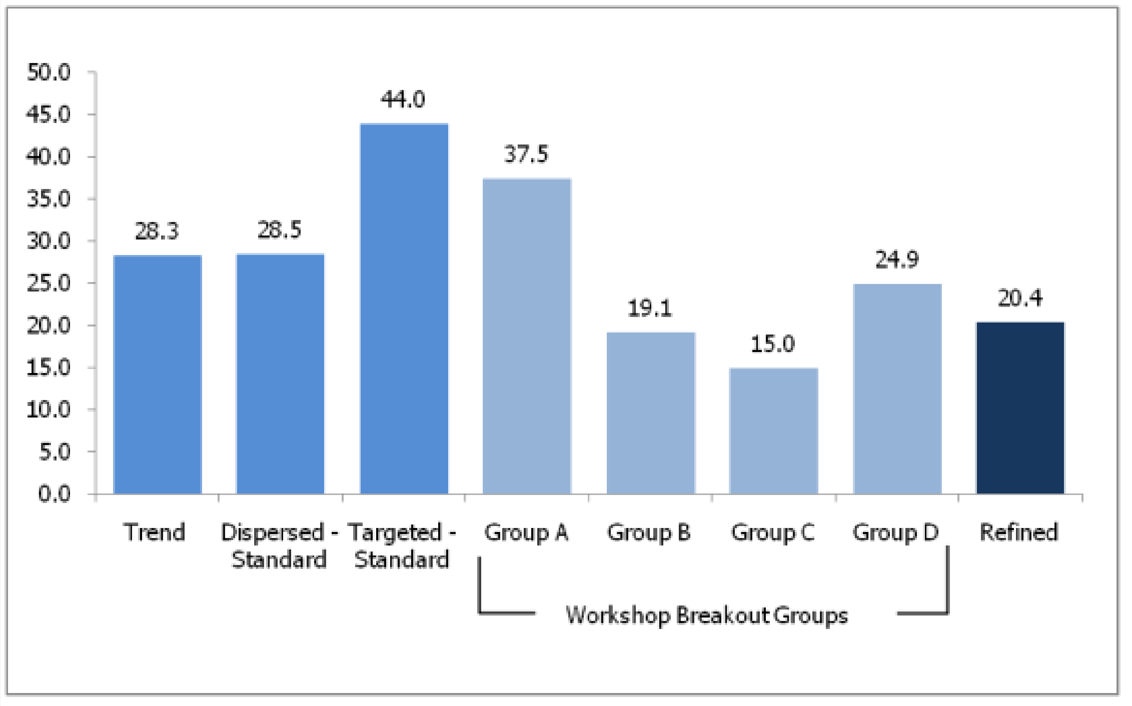
The *vision, goals and objectives* for a transportation planning study usually include more than just transportation topics, encompassing such issues as environmental quality, economic competitiveness, community quality of life, public health, etc. Goals and objectives further define how the vision will 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. One could also envision 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, that 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 adaption are to be considered as part of the planning effort, this step will also include the level and approach toward climate change projections and how highway vulnerability will be determined. (Brand, Mehndiratta and Parody 2000)

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 U.S. to be affected by sea level rise (SLR). To determine the level of impact of SLR to future population on the Cape, local officials and residents participated in a scenario-planning exercise 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.



Percent 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: (Federal Highway Administration, National Park Service and U.S. Fish and Wildlife Service 2011)

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.

Summary

The diagnostic framework in Figure 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. It was 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 relate to actions that can be easily implemented and/or have other benefits. The issue is 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 impacted 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 2, therefore, must be integrated into the agency's standard engineering, operations 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.

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

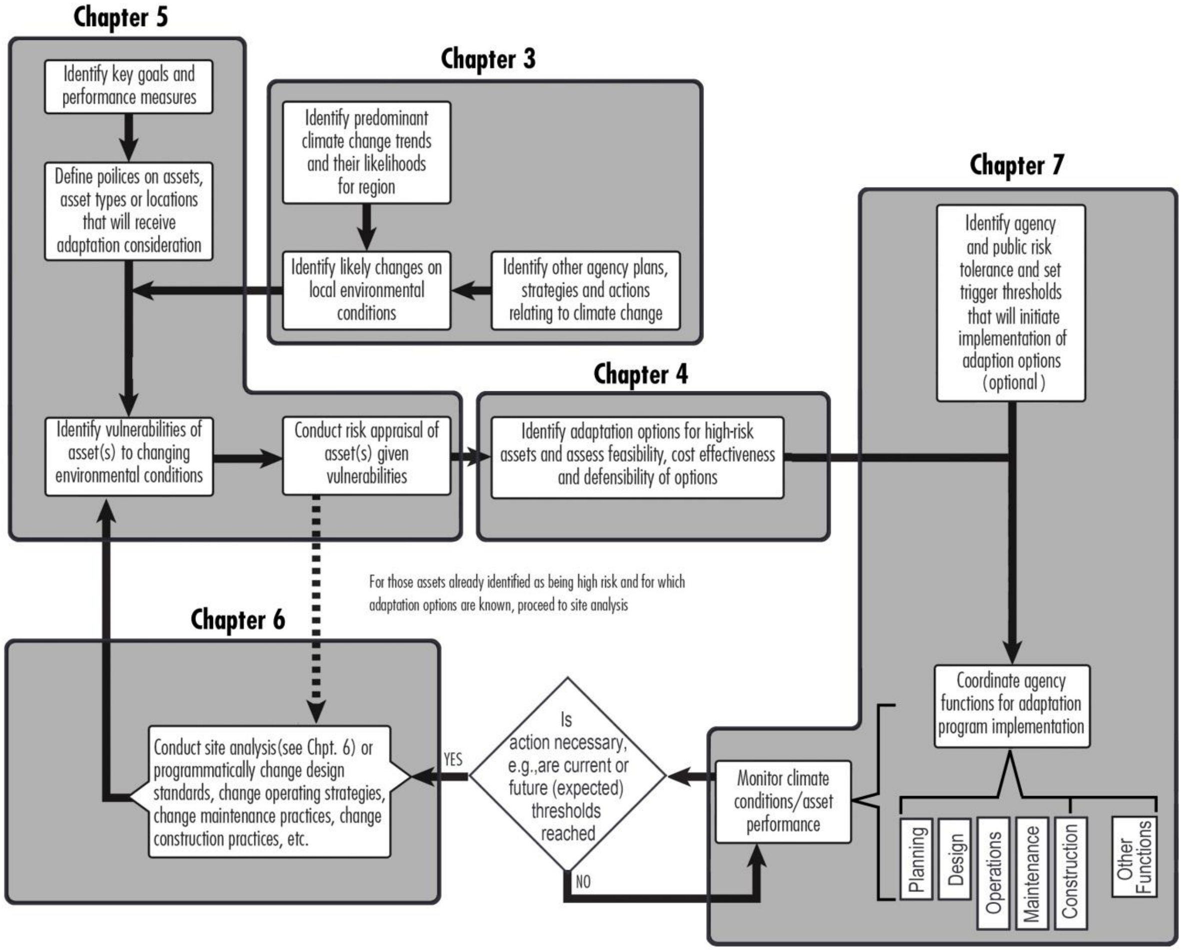


Figure 4: Guide Organization Based on Diagnostic Framework

3. Projected Changes in the Climate

Introduction

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 we *know* the climate is already changing and *will continue* to change, but we do not know *exactly how* it will change, *particularly at the local scale*.** This 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 you want to identify sections of roadway that are vulnerable to flooding, one could examine maintenance records to see where such flooding has occurred in the past or conduct sessions with the agency's operations and maintenance staff to get their input on where problems potentially exist (if you are 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 (GHGs) are called "general circulation models" (GCMs), more precisely, Atmosphere-Ocean General Circulation Models (AOGCMs). 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; Wigley et al 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 the Intergovernmental Panel on Climate Change (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, estimated levels of temperature, precipitation, and other climate variables are found. In reality, a uniform level of weather conditions is not likely to be found across the several hundred miles in each grid box; one would expect different temperatures, amounts of precipitation, etc. 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, one can determine the present-day relationship and use it to estimate how future climate at a specific location will change. This standard procedure involves additional uncertainties because we do not know 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, (as is the case for statistical downscaling) must use inputs from the global models. 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 different 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 may increase, along with other factors such as aerosols that also affect global climate, is uncertain and estimates vary widely.

IPCC 2009: The Intergovernmental Panel on Climate Change (IPCC) developed a set of socio-economic scenarios in 2000 for world population growth, industrial and agricultural development, and energy use from which it calculated expected global GHG emissions. 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 1).

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 1, 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 exception of the optimistic B1 scenario, the global mean temperature (GMT) projections for the A2, A1B and B2 emissions scenarios 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 global mean temperature increase of 1.5°C (2.7°F) over 2010 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. This is most likely due to differences between the scenarios in the emissions of other non-CO_2 GHGs and aerosols.

Table 1: Carbon Dioxide (CO_2) Levels and Temperature Change from Special Report on Emissions Scenarios (SRES) 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	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 2000)

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.

IPCC 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 by first choosing a set of targets and then selecting socio-economically based scenarios (from the large set that is available in the literature) that match the chosen 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 2 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 2 is higher than the CO_2 concentration in Table 1 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 (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.

Table 2: Radiative Forcing in RCPs and Special Report on Emissions Scenarios, Year 2100

RCPs	CO_2 Equivalent (ppm)	SRE Scenario	CO_2 Equivalent (ppm)
RCP 8.5	1,396	A1FI A2 A1B	1,497 1,265 875
RCP 6	779	B2	792
RCP 4.5	586	B1	595
RCP 2.6	453	-	-

Climate sensitivity is estimated by running climate models with historical GHG changes and then comparing the results with observed changes. Note that we cannot use models 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 our 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 ten chance that the true sensitivity is between 1.5°C and 6.0°C. This range represents a factor of 4.

Can We Model Regional Climate?

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. We tend to give GCMs' estimates of long-term <u>average</u> changes 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" from the models' simulation of natural variability. 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 why it is difficult to forecast climate (like the forecast you get for your weather this week) at a regional or local scale is natural variability. This includes factors such as El Niño and many other processes that operate on daily, monthly, annual and decadal time scales. 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 (SSTs) 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, this 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 time scales. 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 discussion below 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 above, the A1FI scenario is the highest of the SRES emissions scenarios that are widely used. Even though the SRES report 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 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 noted above, actual emissions could be lower or higher; therefore, change in climate could be less or more than reported below. However, as discussed below, by 2050, the projections from the A1FI, A2, and A1B emissions scenarios do not differ substantially.

Temperature

Figure 5 presents average change in temperature in the U.S. 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 1). 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 U.S.

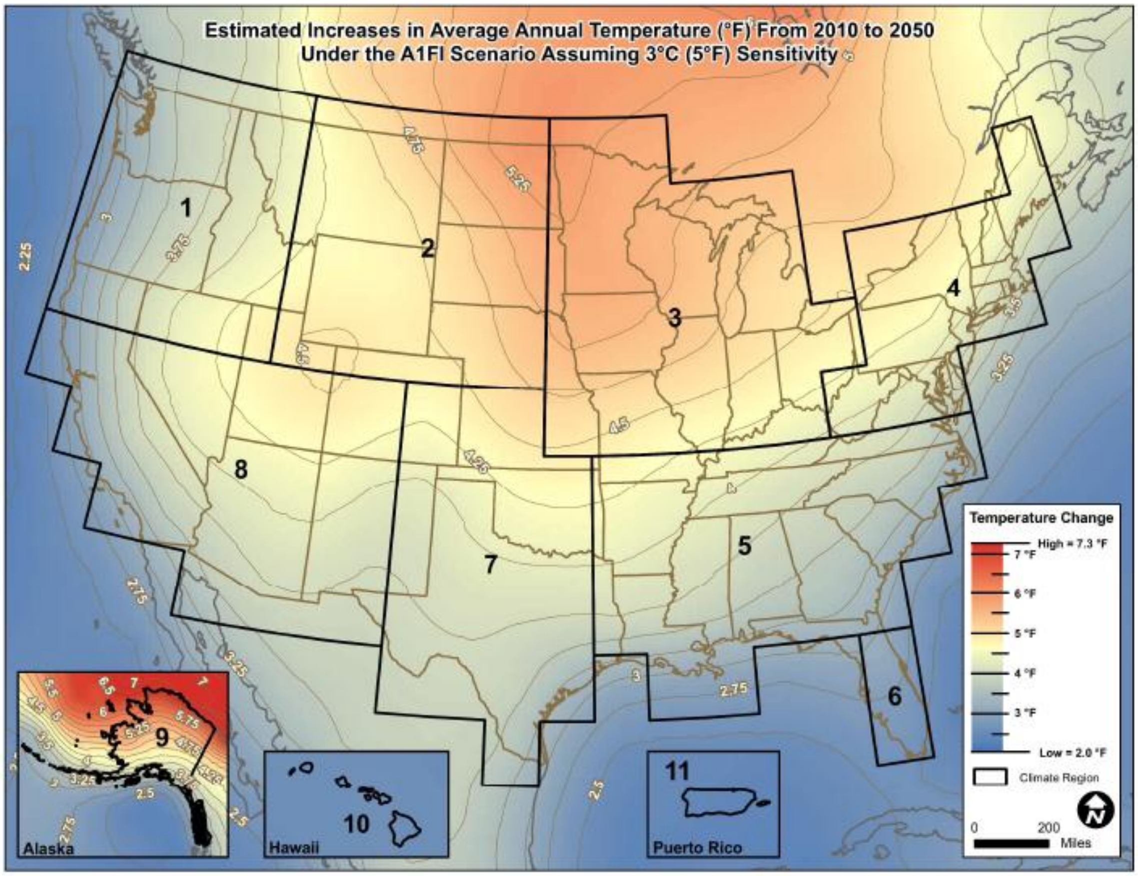
Note that in the last 50 years, average U.S. temperatures, including Alaska, increased by around 1.2°C (2°F), which means that temperatures in the lower 48 states increased by less than 2°F. (Karl et al 2009) The projected temperature change would result in an approximate doubling of the past rate of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

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 us determine which



Note: This figure presents change in temperature across the US. 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 5: Estimated Increases in Temperature (°F) in 2050 Relative to 2010 Using A1FI Scenario, 3°C Sensitivity

areas are likely to become wetter and which ones are likely to get drier. In some areas, we can project whether likely changes in average total precipitation will increase or decrease, 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. This is particularly true for “convective” precipitation, e.g., summer thunderstorms. 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. We do not know whether precipitation will increase in other areas such as the Northwest or the Southeast. Figure 6 displays average annual 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, we should not put too much weight on individual model projections. The result of the averaging of models gives a more robust picture, but the fact that there are substantial inter-model differences implies that even the average is still subject to considerable uncertainty. So,

Expected Climate Changes in Iowa

The Iowa Climate Change Adaptation and Resilience report 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.

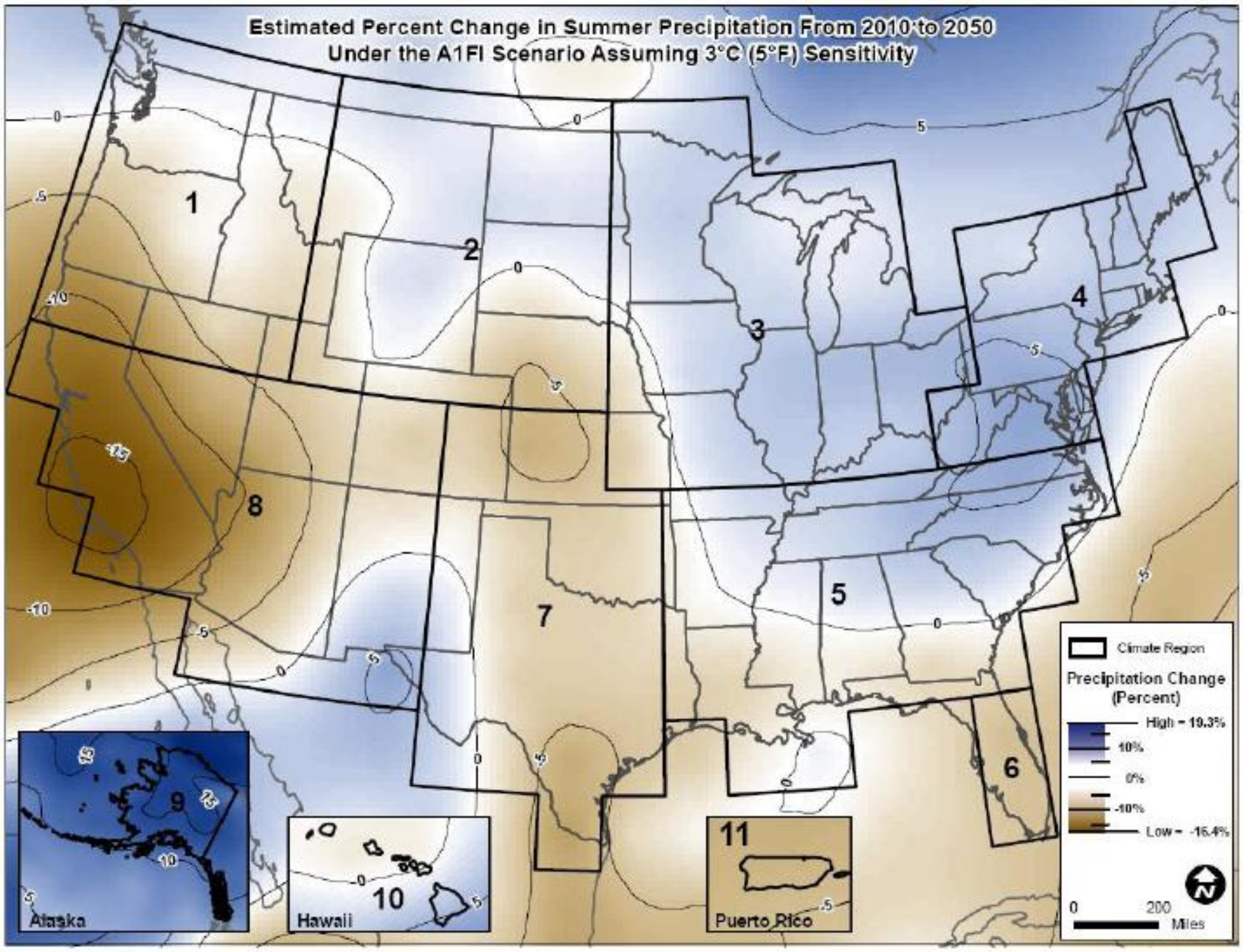
Annual temperatures are expected to increase by 2.5 to 7.2°F."

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."

http://www.epa.gov/dced/pdf/iowa_climate_adaptation_report.pdf



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 6: Percentage Change in Annual Precipitation
in 2050 Relative to 2010 Using A1FI Scenario, 3°C Sensitivity

while the models tend to show a drier Southwest and a wetter Northeast and Midwest, the differences across the models mean we cannot 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 U.S. 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 above, 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

It is not only average conditions but the frequency and magnitude of extremes that 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 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 five-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 (SST). As SSTs rise, we can expect hurricanes to

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 events could affect natural gas supply in Massachusetts." Other impacts included:

"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."

http://www.mass.gov/eea/docs/eea/energy/cca/eea-climate-adaptation-chapter5.pdf 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 we could see fewer hurricanes, but the ones we do see, particularly the most powerful ones, will be even stronger. (Emanuel et al 2008; Knutson et al 2010) This suggests that over a timescale of decades, we could see more destructive hurricanes, but fewer of them. There is also substantial year-to-year and decade-to-decade variations in hurricane frequency. (e.g., Landsea 2007)

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 in (1.5 to 2 mm) per year, but since the early 1990s have been rising at a rate of 0.12 in (3 mm) per year. Given that rates of sea level rise can fluctuate naturally, it is not clear whether the apparent acceleration in the rate of sea level rise 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 in to 2 ft (0.2 to 0.6 m) 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 ft (7 m) or more, but it would take centuries to millennia for that amount of sea level rise 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 ft (1.5 to 2 m) by 2100 (e.g., 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 ft

(0.8 m) relative to 1990 and that sea level rise will not exceed 6.6 ft (2 m) by 2100. A recently released report by the National Research Council projects that mean sea level will rise 3.1 to 9 inches (8 to 23 cms) by 2030 relative to 2000, 7 to 18.5 inches (18 to 48 cms) by 2050, and 19.6 to 55 inches (50 to 140 cms) by 2100. (Committee on Sea Level Rise in California, Oregon, and Washington 2012) Using MAGICC (Wigley 2008), a scenario yielding 31.5 in (0.8 m) sea level rise by 2100 would have approximately 10 inches (25 cms) of sea level rise by 2050 relative to 1990 [8 inches (20 cms) relative to 2010].

Note that the sea level rise 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 sea level rise to vary by as much as half a foot (0.15 m). (Meehl et al 2007; Bamber et al 2009)

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." 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." The plan notes that sea level rise will most likely 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 sea level rise might require "entirely new drainage systems in low-lying cities with drainage that is pump-driven rather than gravity-driven."

http://resources.ca.gov/climate_adaptation/docs/Statewide_Adaptation_Strategy_-_Chapter_10_-_Transportation_and_Energy_Infrastructure.pdf

Of perhaps greater importance for relative sea level rise 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 of 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 ft (0.9 m) 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 Can I Get Climate Data and Advice for My 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 datasets 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.

GCM 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 are the GCM runs done for the IPCC Fourth Assessment Report published in 2007 (Solomon et al 2007). PCMDI is collecting GCM runs being done for the Fifth Assessment Report (CMIP5).

A simpler approach is to use the tool M/S that was used in this research. M/S provides parameterized output based on GCMs, not raw GCM projections. M/S 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. What is typically done is to use the change in climate as estimated by GCMs. The increase in temperature or change in precipitation estimated by the models can be combined with observed climate datasets 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. This 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 datasets derived by applying statistical downscaling techniques. One version of the statistical downscaling method is employed in the user-friendly software "SDSM." The Statistical Downscaling Model may be obtained at http://co-public.lboro.ac.uk/cocwd/SDSM/ from Loughborough University in the United Kingdom. One will have to master the downscaling technique to be able to run the model and produce downscaled estimates of climate change, although applying SDSM will probably take less time than running PRECIS.

What Do I Need to Know 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 above, even with the same assumptions about GHG emissions, different climate models will give different projections of change in global and regional climate. We assume that each climate model run is a *plausible* estimate of how climate *could* change. Since there is so much variation across the emissions scenarios and the models, the best we can offer 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. Be sure to capture such a range on variables that are particularly important such as precipitation and temperature. So, if you are most concerned about how precipitation can change, then you 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 could be used. For these shorter timescales, historical climate information averaged over recent decades. Essentially by doing this, one is taking 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 such 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 dataset to simulate natural variability. Changes in temperature and precipitation (and other variables) simulated by a model could be combined to historical observations, say from 1981 to 2010 as discussed above. This assumes the variability in climate over recent years will continue in the future, but at least in a general sense whether it is warmer, wetter or drier on average can be projected.

Emissions Scenario

As noted above, 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 to 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 1, 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 up to 2050 is reasonable. Beyond 2050, it may be prudent to use more than one emissions scenario if able to do so. An important reason for using a wide range of emissions scenarios is to find out how your 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 and 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) examining how well the model simulates current (observed) climate, and 2) 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. One should also consider whether these models capture a wide range of change in temperature. 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 should include a relatively wet and relative dry model run, and either a single model run in the middle of the distribution or an average of all of the models. One may also wish to run several emissions scenarios, particularly if change in climate in the latter half of this century is being examined so as to understand how climate change impacts could differ.

4. Possible Impacts to the Highway System and Natural Environment and Agency Responses

Introduction

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 both infrastructure and operations & 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 found 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 impact 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 blow-outs 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 impact highway systems. The increase 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 over what occurs today, but possibly increase the incidence of slippery roads; and the incidence of frost heave and road damage caused by snow and ice in southern locations is likely to decline. However, they 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 U.S. annually.

Expected Climate Impacts in Washington State

The Washington State DOT (WSDOT) 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."

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.

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, alligator cracking, AC 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 – of both rain and snow - will vary widely across the various regions in the U.S. These changes are expected to impact highways in several ways, depending on specific regional precipitation levels and geographic conditions. Given the prevalence of drought in the U.S., with 20% of the country reportedly in extreme drought and 60% in some degree of drought, 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.

<u>Impacts on Operations/Maintenance</u>: 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, increased 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 US 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.” (US Global Climate Change Research Program 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. 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 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 is focused 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 listing 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 impact 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 impacted 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 sea level rise as being the most important challenge they face. An estimated 60,000 miles of coastal highway in the U.S. 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 fact that 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.

How Could Greater Hurricane Intensity Affect Road Assets?

The intensity of the most powerful hurricanes are 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 two 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.

Impact to Operations/ Maintenance: More intense storms will leave behind greater volumes of debris, 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, sea level rise may render existing evacuation routes less useable in future storms.

How Could Climate Stressors Impact 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 mitigation of flora and fauna and 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: (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;
- Deserts and dry lands becoming hotter, and drier;
- Coastal and near-shore ecosystems, already under multiple stresses, will be made more vulnerable by ocean acidification; and
- 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 storm water 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,

Tropical Storm Irene’s Impact on Vermont

Vermont was one of the states impacted by Tropical Storm Irene. According to the Vermont Agency of Natural Resources, rainfall totals of 3-5” were recorded throughout the state, with many areas receiving more than 7”, 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, the Vermont Agency of Transportation, the state’s DOT, had in 2007 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:

- “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 storm water systems to be designed and maintained to adequately handle the associated increased flow, sediment and debris transport
- With increased stream flow, comes increased bridge scour
- 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 ROW. 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 ROW vegetative management and stream bank longevity”

http://www.anr.state.vt.us/anr/climatechange/Pubs/VTCCAdaptTrans_DRAFT.pdf 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 – Invasive species - non-indigenous species - will become much more difficult to control, as changing climate conditions render the "native" species less suited for a given region. 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.

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:

- 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.
- 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 storm water 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 3 illustrates the range of actions that can be considered for both operations/maintenance and design considerations, as indicated for the Maryland State Highway Administration. (2012) Note that the table contains information for each action that includes:

1. ***Climate threats*** the action item addresses:
    a. High temperature extremes [High temp.]
    b. Floods
    c. Sea level rise
    d. Slope failure
    e. Tropical storm
    f. Wind
    g. Winter storms
2. ***Focus of the action***, which describes what the action is meant to address.
3. ***Co-benefits*** that note any additional benefits to the action item beyond the adaptation benefits, including:
    a. System reliability
    b. Safety
    c. Morale
    d. Efficiency
4. ***Cost avoided*** (benefit), which provides a rough dollar value estimate of the average annual costs to be saved by implementing the adaptation action.

Table 3: Maryland’s Actions Listed in the State Climate Change Adaptation Policy

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 back-ups 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 GIS database of existing flooding hot spots
- Create a 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 NOAA
- 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 SOCs and 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

Take operations, maintenance, and administrative actions now which enhance the response to and prevent impacts from extreme weather events—Preventative 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 MDE to streamline environmental regulations relating to culvert cleaning
- Coordinate with MPOs on climate adaptation initiatives
- Install monitoring devices on vulnerable slopes
- Review erosion and sedimentation standards
- Increase tree-trimming activities to meet needs

Take operations, maintenance, and administrative actions now which enhance the response to and prevent impacts from extreme weather events—Administrative Actions

- Provide overtime instead of comp time for severe weather response
- Clarify departmental responsibility for bridge approaches

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 SHA/MdTA climate projections (climate models, downscaling technique, & 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-àvis 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 into 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 BAU) • 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)

5. Cost, which provides a rough dollar value estimate of the costs of implementing the action item statewide.

6. Timeframe to initiate the action, including:
   a. 2012-2013
   b. 2014-2015
   c. 2016 or beyond

7. Responsibility for implementation by agency office, which includes a lead or support role. (Note: 16 different agency offices were given some level of responsibility in implementing the policy).

Each agency should examine its own portfolio of actions depending on 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 4 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. This underscores the importance of considering climate change in all phases of transportation decision making where vulnerability is expected. A long-range perspective on possible threats to infrastructure in the future and the how 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 Intergovernmental Panel on Climate Change's *Special 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. (Intergovernmental Panel on Climate Change (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.

Table 4: 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 blow-outs; • 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; • Structures will freeze later and thaw earlier with shorter freeze season lengths • Increased freeze-thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces; • Permafrost thawing leads to increased slope instability, landslides and shoreline erosion 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, 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.

	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 at risk of subsidence/heave; • Drought-caused shrinkage of subsurface soils	• 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); • Closure of roadways and underground tunnels 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, tall structures at risk from increased wind speeds	• The number of road closures due to flooding and washouts will likely rise; • Erosion at road construction project sites as heavy rain events take place more frequently; • Road construction activities could be disrupted; • Increase in weather-related highway accidents, delays, and traffic disruptions; • increase in landslides, closures or major disruptions of roads, emergency evacuations and travel delays; • 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

	Climatic/ Weather Change	*Impact to Infrastructure*	*Impact to Operations/ Maintenance*
Sea level rise	**Sea level rise**	• Higher sea levels and storm surges will erode coastal road base and undermine bridge supports; • 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); • Loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action	• Coastal road flooding and damage resulting from sea-level rise and storm surge; • Underground tunnels and other low-lying infrastructure will experience more frequent and severe flooding;
Hurricanes	**Increased hurricane intensity**	• Stronger hurricanes with more precipitation, higher wind speeds, and higher storm surge and waves are projected to increase; • 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

5. Vulnerability and Risk Assessments for Climate Adaptation

Introduction

Although each step in the adaptation planning process is important from the perspective of conducting an adaptation study, there is one step in particular that 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 2, risk assessments are typically conducted subsequent to the asset vulnerability analysis for the purpose of better understanding the nature of potential climate impacts on infrastructure. Ideally, risk assessment leverages information from the vulnerability analysis, 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 (such as a flood exceeding a certain stages and consecutive days of higher than 100 degree temperatures) results in asset failure or sufficient damage to reduce its functionality. The vulnerability can thus be measured as the probability that the asset will fail given climate stressors ("there is a 90% 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) that asset failure. 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:

Risk = Probability of Climate Event Occurrence x Probability of Asset Failure x Consequence or Costs

One can see from the equation for risk that low probability climate events (e.g., a category 5 hurricane hitting your community) but 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 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. For example, the FHWA Conceptual Model (FHWA 2012), ICLEI's "Preparing for Climate Change: A Guide for Local, Regional, and State Governments" (Center for Science on the Earth System and King County (WA) 2007), the UK Climate Impact Program on Climate Change Risk (UK Climate Impacts Programme 2003) and the NYC Panel on Climate Change's "Climate Change Adaptation in New York City" (New York City Panel on Climate Change 2010) have each adopted the multi-factor approach to risk.

Although many risk frameworks consider "probability of impact" as a composite factor, others, such as the NYC Climate Task Force's "Three Dimensional Climate Change Risk Assessment Matrix" (shown in Figure 7), looks at the components of probability individually. For purposes of this guide, two approaches to risk assessment will be presented dependent on whether you have access to or are willing to develop numerical probability information. It is worth noting that very few of the risk assessments in the transportation sector conducted to date have actually assigned numerical probabilities to these risk factors although research is moving in this direction.

In order to determine vulnerability as part of an adaptation assessment one must first determine which assets, asset types or locations are to be targeted. This is the case simply because a transportation agency

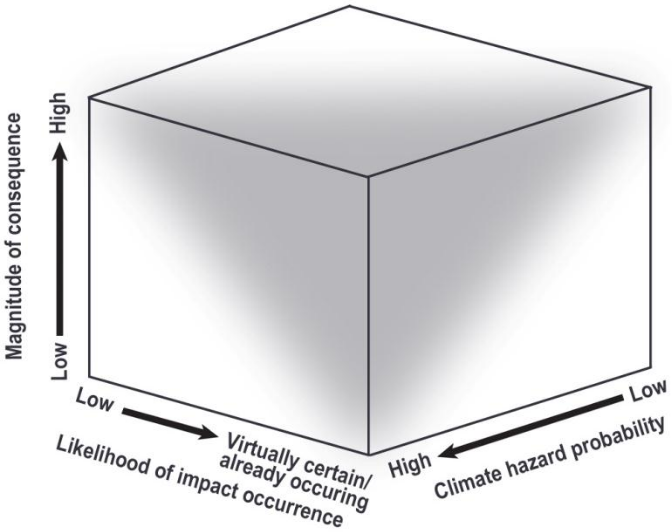


Figure 7: Three-dimensional Climate Change Assessment Matrix

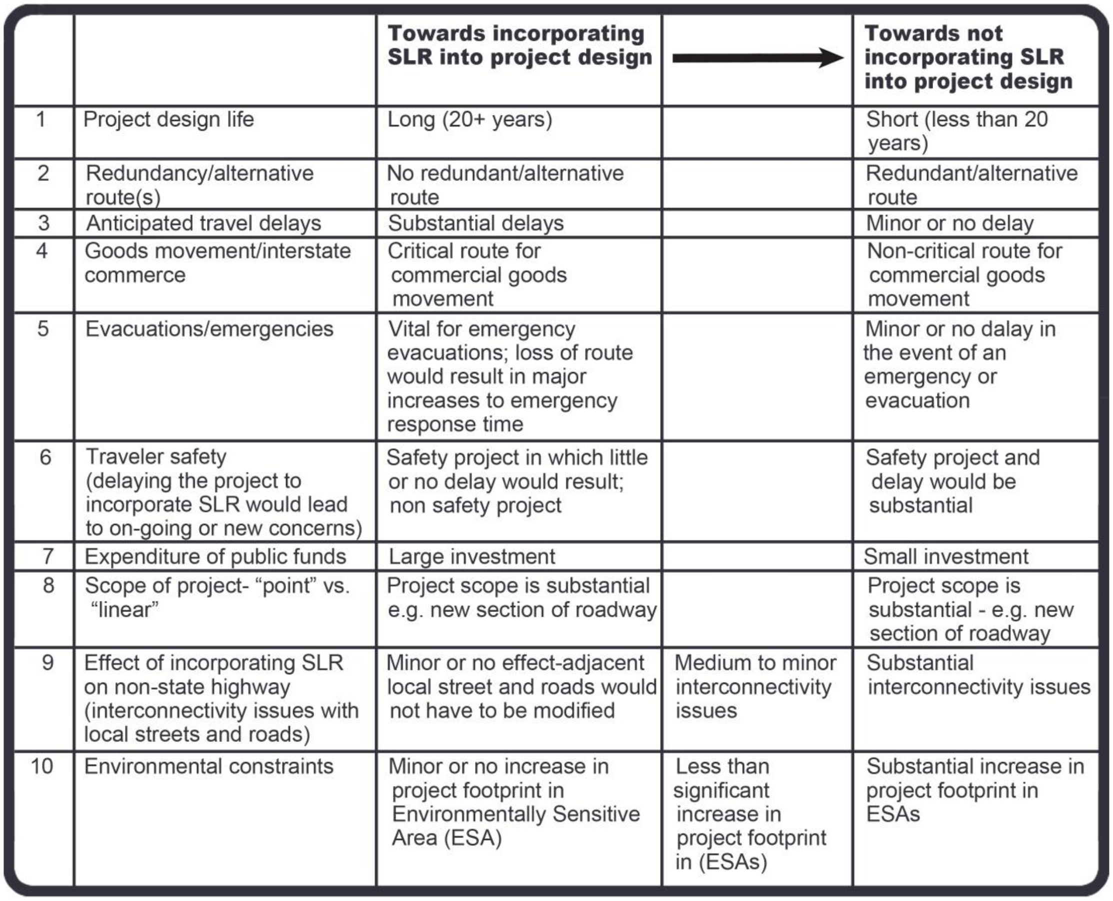
will not have enough resources to climate-proof all of its assets. As shown in the diagnostic framework (Figure 2), several steps precede the vulnerability and risk appraisal steps. Understanding the likely climate stressors is clearly important for understanding potential threats. However, as shown in the diagnostic framework it is also important to define the focus or purpose of the adaptation assessment process. Are you going to only focus on assets that are considered most important from an interstate commerce perspective? Or are you going to identify the most vulnerable assets no matter where in the network and invest in asset protection? Or are you 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 sea level rise 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 sea level rise?
2. Can 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. Table 5 shows the "balance" between either considering sea level rise or not. 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 sea level rise adaptation actions into project design.

Table 5: 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 dalay 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 could include conducting an engineering assessment of critical assets that might be vulnerable to climate stressors. This approach, in essence, "piggy backs" adaptation strategies on top of other program functions (e.g., maintenance, rehabilitation, reconstruction, etc.).

What If We Don't Have Probabilities?

Although it is likely that some climate change event is going 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 Intergovernmental Panel on

Climate Change (IPCC) emissions scenarios (Special Report Emissions Scenarios) and General Circulation Models (GCMs) do not provide such probabilities; the IPCC's official position is that each emissions scenario has an equal probability of occurrence.

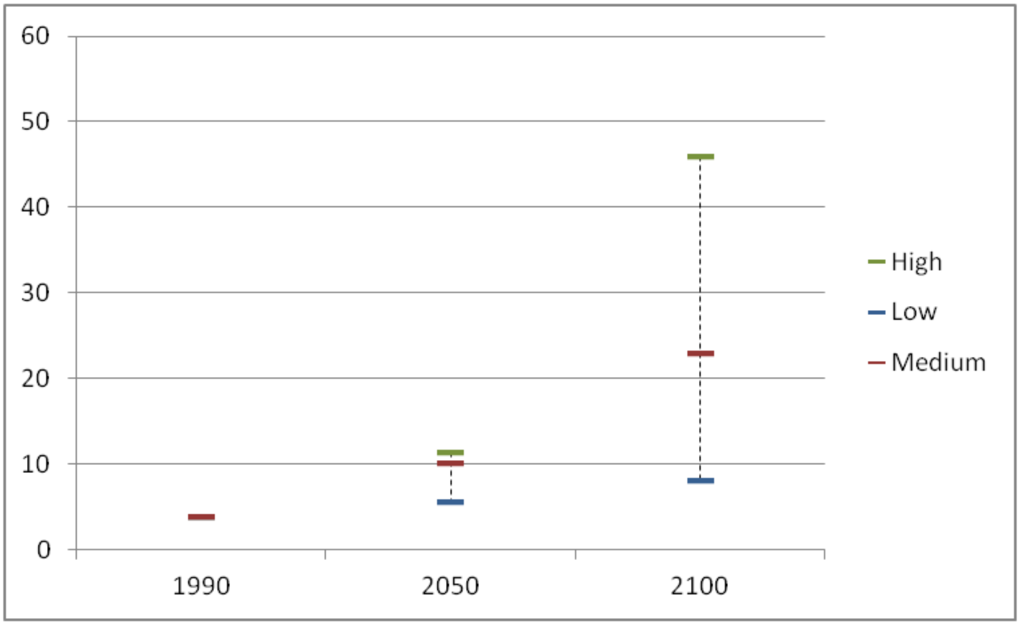
Due to the difficulties in identifying probabilities, climate risk is often characterized very broadly and qualitatively (e.g., high, medium or low, or on a scale from 1 to 10). Obtaining a plausible characterization of likelihood—one that balances accuracy with precision—is a challenge inherent in climate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

Several recent studies have illustrated alternative approaches to handling the uncertainty in climate events occurring. Each of these provides a possible option for considering the likelihood of climate events occurring.

1. *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 sea level rise 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 (CO-CAT) 2010) and used by the Bay Area's Metropolitan Transportation Commission (MTC) in its "Adapting to Rising Tides" report. (Metropolitan Transportation Commission 2011). Another way of looking at this is that since the climate will continue to warm indefinitely until CO2 levels are stabilized, one can safely assume that any threshold will eventually be reached. Washington DOT's pilot project for the Federal Highway Administration's (FHWA's) conceptual adaptation model chose to eliminate timeframe when conducting scenario analysis, in other words they assumed the climate stressor was going to happen and did not worry about when. (Washington State DOT 2011)

2. *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 8, below) (North Jersey Transportation Planning Authority 2011). Highly critical assets—those essential to system functionality, for example—would be assessed for potential vulnerability

and thus risk given the asset was determined to be “critical”) 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 1/10,000 year storm event).



Source: (North Jersey Transportation Planning Authority 2011)

Figure 8: Climate Stressor Brackets for Average Annual Number of Days Equal to or Exceeding 95°F in Atlantic City, NJ, 1990-2100

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 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 multi-dimensional, 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:

- **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:** Although not measured in dollar terms, changing public confidence in an agency's ability to deal with emergency situations 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 We Portray the Results of Risk Assessment Without Probabilities?

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

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 multi-attribute prioritization process. The screening steps consist of:

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 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 (Caltrans, 1994).

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 = $\sum$(Attribute Weight)(Global Utility Function Value)

Impact = $\sum$(Attribute Weight)(Global Utility Function Value)

Vulnerability = $\sum$(Attribute Weight)(Global Utility Function Value)

Caltrans made further adjustments based on several considerations including:

- 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

Caltrans' Risk-based Decision-making for Bridge Seismic Retrofit, cont'd

Table: Summary of Multi-Attribute Decision Procedure Elements Showing Weighting Percentages Applied to Each Attribute

Hazard Criteria	
Attributes	**Weight**
Soil Conditions	33%
Peak Rock Acceleration	38%
Seismic Duration	29%
Impact Criteria	
Attributes	**Weight**
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%
RTE Type on Bridge	7%
Critical Utility	10%
Facility Crossed	7%
Vulnerability Criteria	
Attributes	**Weight**
Year Designed (Construction)	25%
Hinges (Drop Type Failure)	16.5%
Outriggers, Shared Column	22%
Bent Redundancy	16.5%

Risk assessment matrix: Figure 9 is offered by the Federal Highway Administration 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). Washington State DOT used this approach in identifying which of its assets were at highest risk for different types of climate stressors. Figure 10 shows how the different WSDOT assets could be rated with respect to risk. (Washington State DOT 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 UK 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 (Highways Agency and

Parsons-Brinkerhoff 2008). Each of these criteria was ranked on the basis of a high (3 points), medium (2 points) or low (1 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 one week; two points if it was to last one day to one week; and one point if it was less than one day. Based on the risk appraisal and a combination of the different risk factors, the following concerns 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).

First Tier

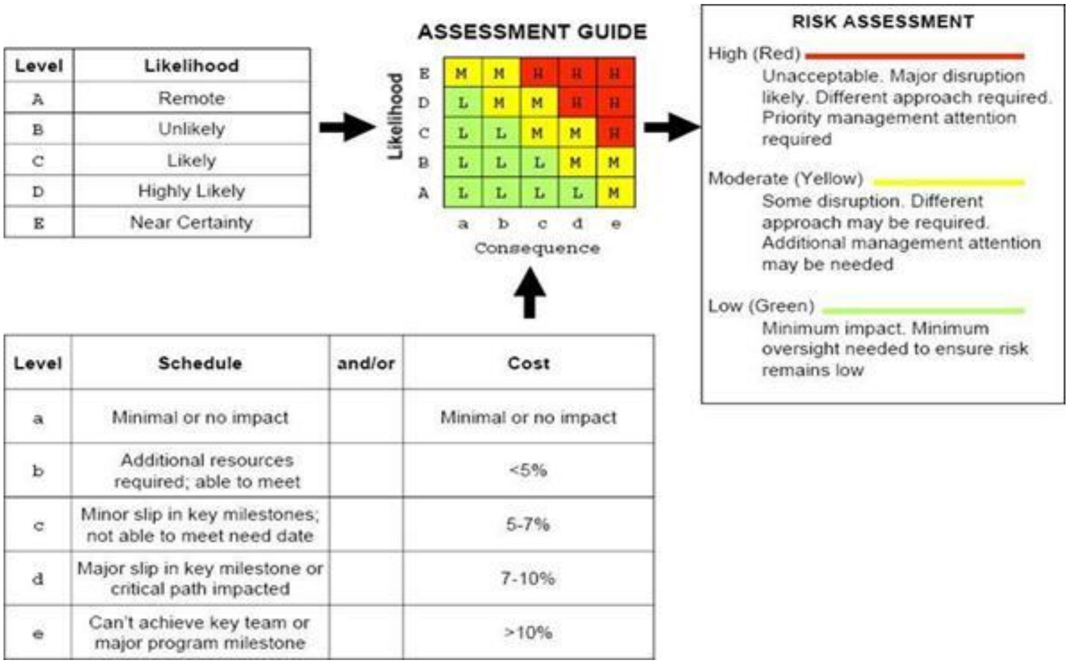
- Pavement skid resistance
- Identifying best ways of investing resources/investment appraisals

Second Tier

- 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

Third Tier

- Pavement materials specification and construction details
- Design of pavement foundations
- Design of bearings and expansion joints
- Surface water drainage
- Attenuation and outfalls



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

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%

RISK ASSESSMENT

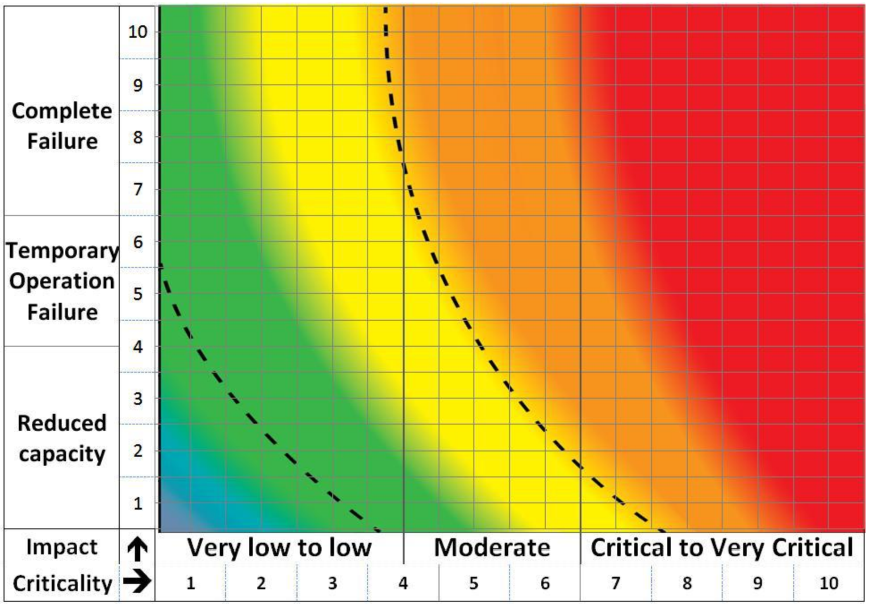
High (Red) 🟥
Unacceptable. Major disruption likely. Different approach required. Priority management attention required

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

Source: (FHWA 2012a)

Figure 9: An Approach for Considering Risk in Decision making



Source: (Washington State DOT 2011)

Figure 10: Washington State DOT's Assessment Approach for Identifying Assets at Risk

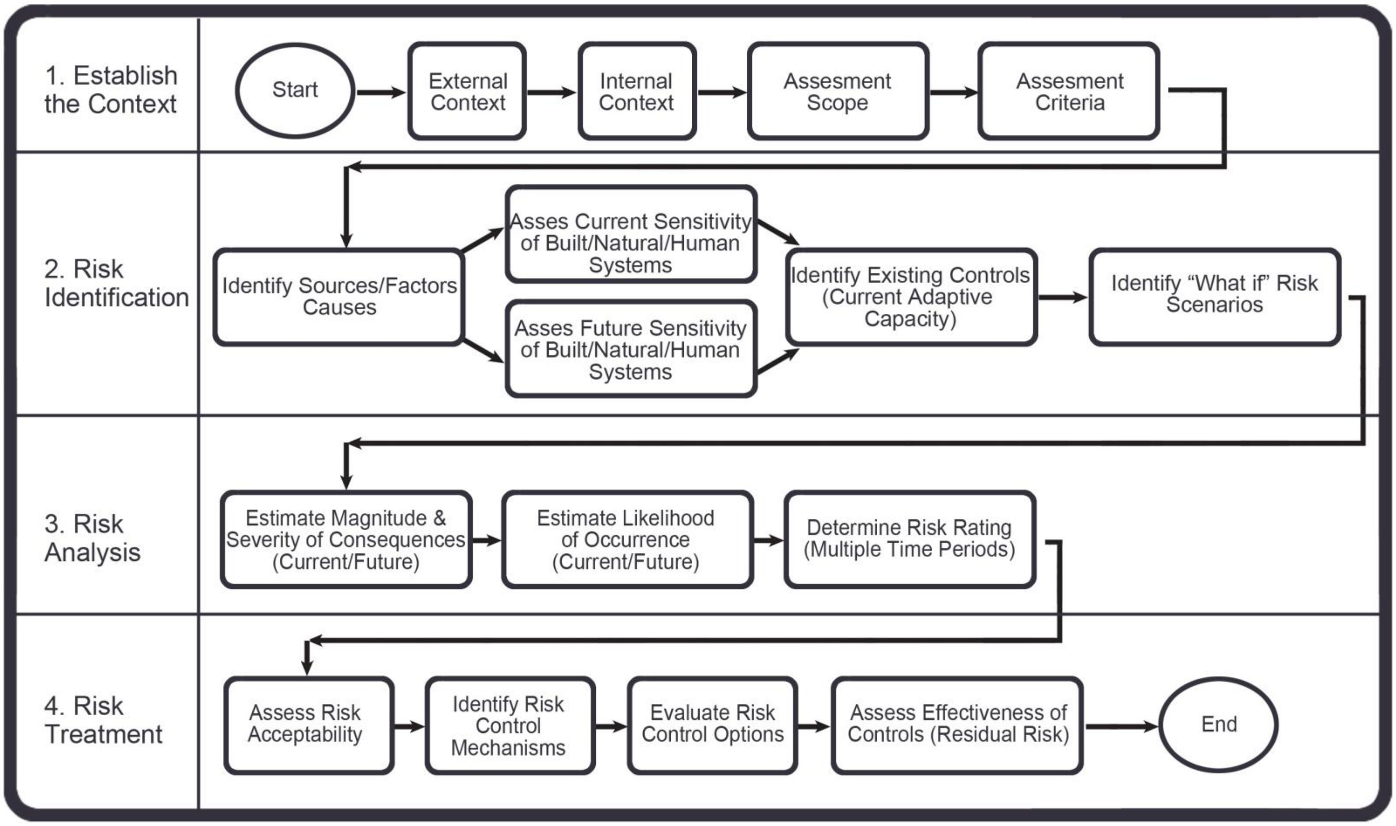
- Pavement maintenance
- Flooding

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

Probability ranges: If one cannot determine an exact probability for an event occurring, 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, one can estimate with some level of confidence that the probability of the event will fall within a 55% and 90% probability range. This could then be labeled a "highly likely" probability.

For example, the City of Toronto has developed an Environmental Risk Assessment Process and Tool 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" (see Figure 11). (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 Figure 9 and Figure 10 along with probability ranges, that is, "almost certain" (90 to 100% probability), "very likely" (55 to 90%), "likely" (30 to 55%), 'unlikely" (5 to 30%), and "rare" (0 to 5%).

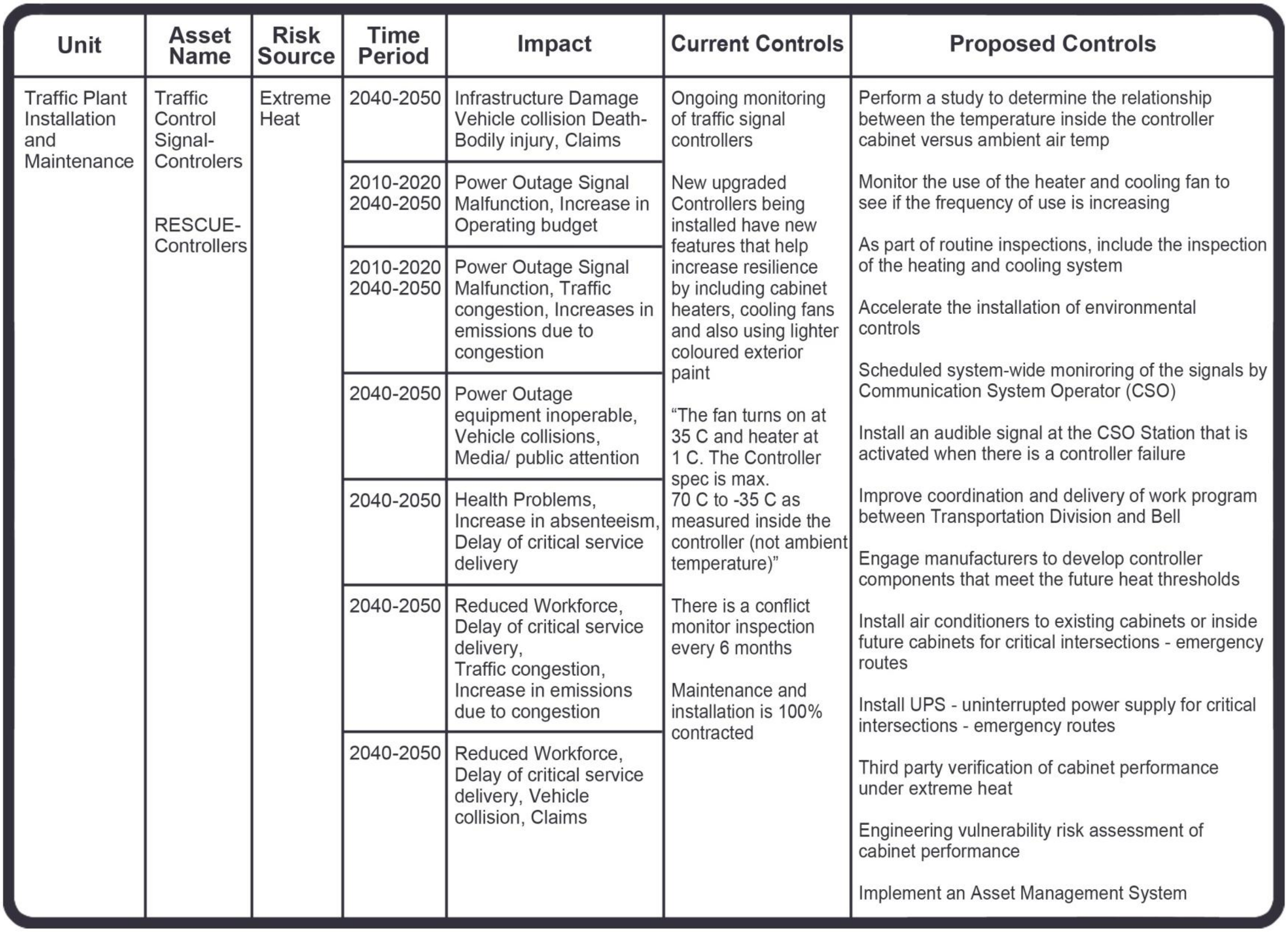
The results of the tool application are shown in Table 6 and Figure 12. As shown in Figure 12, Toronto has used the tool to determine the overall risk for the key assets that it is responsible for. This includes road operations, road assets and intelligent transportation systems. The types of actions that have been taken in response to this process include such things as 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 rainfalls and landscaping with drought-resistant plants.



Source: (City of Toronto 2011)

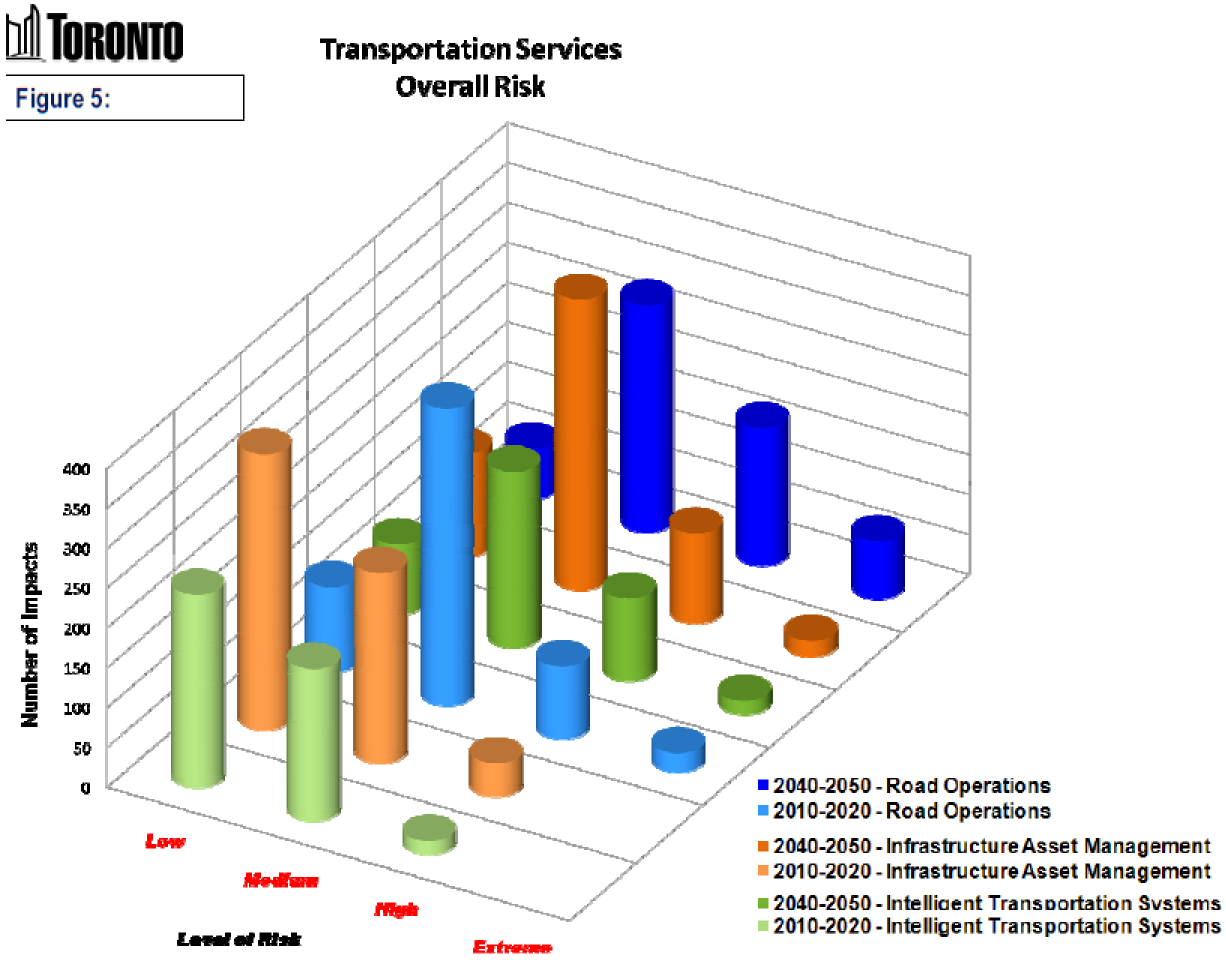
Figure 11: Adaptation Planning Process in Toronto

Table 6: Example Assessment of Transportation Assets in Context of Extreme Heat, Toronto



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)



Source: (City of Toronto 2011)

Figure 12: Overall Transportation System Risk Assessment to Climate Change, Toronto

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…

1. **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.

2. **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 sea level rise 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, one could use the estimates of climate event occurrence that result from such studies.

3. **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.

4. **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. One could use (with necessary cautionary statements) the distribution of the individual models 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 forecasted period, this **does not mean** there is an 80% chance of such an outcome, but it does show that most models project such a change. Such information can be considered in analysis 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…

1. **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.
2. **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.
3. **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 2011) 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 et al 2002)

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 2011), it is possible "to assign probabilities to the events in each single socio-economic and climate scenario even though it is not possible to assign probabilities to the scenarios themselves occurring." Their example is sea level rise 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. One could discount these costs and use benefit/cost analysis 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 sea level rise 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:

- 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 above)
- 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 as assessment of future change?
- What is the difference in cost associated with adaptation strategies added to the design to insure 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 (system or 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 to what extent the adaptation planning effort and in particular the identification of risk will be part of a much broader planning process, or one primarily oriented to the technical details of a broadened definition of asset management.

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6. Climate Change and Project Development

Introduction

The previous sections 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 efforts at doing so 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 U.S. 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 questions or a checklist of 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 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.

Suggested Approach

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 above, most of the approaches developed to date have consisted of a checklist of questions relating to the potential change in the affected environment. The approach suggested in this *Guide* is similar, but related to the diagnostic framework in Figure 2.

For projects with an expected project lifespan over “x” (say 30) years, document your answers to the following questions and recommend appropriate action during the more detailed engineering design phase of the study.

1. What climate stressors will affect your 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 potential 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 (WSDOT) is one of the first state transportation agencies in the U.S. to develop project development guidance on climate change. (Washington State Department of Transportation 2012) As noted in the guidance, WSDOT "acknowledges that effects of climate change may alter the function, sizing, and operations of our facilities." 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. Specific steps are recommended.

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 draft language to be incorporated into project initiation documents and environmental reports, where appropriate.

> "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) 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 is 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 Does One Do Adaptive Engineering Design?

What pipe diameter is necessary for a culvert to function properly? What asphalt mix will minimize pavement lifecycle 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 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, storm water infrastructure, slopes/walls, and pavement. Due to their size, these tables are provided in a CD-ROM attached to this report. For purposes of illustration, the tables relating to culverts are presented in this section.

Table 7 to Table 9 present the information that can be found in the adaptive design approach for culverts. Table 7 presents information on the input variables that are used to calculate key design parameters. For example, Table 7 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 8 presents information for new infrastructure adaptation options. For example, Table 8 indicates that for more extreme rainfall events and greater snowfall depths one could consider increasing culvert size, use a small bridge instead of a culvert or use a larger scour pool or rip rap. In addition, the table shows how one could incorporate future flexibility into a traditional design that might have to be retrofit in the future given changed flow characteristics.

Table 9 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 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 was synthesized from best practice for each type of asset or facility. For those states that have their own design standards or guides that differ from what is presented, they are encouraged to modify the tables as appropriate. Information is presented for both new infrastructure and for modifying existing infrastructure.

The adaptive engineering analysis described below 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

Table 7: Culvert Design Climate Dependent Input Parameters

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 Clasius-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 Clasius-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

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[1] The Clasius-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; National Research Council, 2011). While the interactions between 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 U.S.

Table 7: Culvert Design Climate Dependent Input Parameters [*Continued 1*]

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 [Continued 1]	***More extreme rainfall events [continued]***	Stream flows (2 -100 year recurrence intervals) [*continued*]	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 ~~(see Table 6.1a)~~
			Stream gage analysis	Shape of historical data curve[5]	USGS or local sources	**Preferred:** Utilize stream gage analyses with data adjustments using regional curves with considerations for climate non-stationarity **Alternative:** Utilize theoretical models instead

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[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 7: Culvert Design Climate Dependent Input Parameters [*Continued 2*]

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 [Continued 2]	***Greater snowfall depths***	Stream flows (2 -100 year recurrence intervals)	Regional regression curves	Shape of regional curve[6]	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 gage analysis	Shape of historical data curve[7]	USGS or local sources	**Preferred:** Utilize stream gage analyses with data adjustments using regional curves with considerations for climate non-stationarity **Alternative:** Adjust results of historic gage analysis by a percentage correlated to anticipated snowpack increase

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[6] 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.

[7] 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 7: Culvert Design Climate Dependent Input Parameters [*Continued 3*]

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 forecasted from a revised water budget model **Alternative:** Investigate historic response of lake levels to years with high annual precipitation. Extrapolate lake level trends to projected annual precipitation levels.

Table 7: Culvert Design Climate Dependent Input Parameters [*Continued 4*]

First-Order Climate Variable (Column 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 [Continued]	***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 historic 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 lifespan based on climate research
	Ocean acidification	-	-	Water pH	Water samples	**Preferred:** Use projected maximum pH over asset lifespan from climate research

Table 8: 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 ROW and access routes to allow for culvert retrofit	Low to moderate Moderate	-
	Greater snowfall depths		Larger scour pools and larger rip-rap	Low		Use of a bridge instead of a culvert		
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[8]	Obtain ROW and access routes to allow for culvert retrofit	Low to moderate	-
			Consideration of more saltwater resistant materials in currently freshwater environments	Low				

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[8] 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 8: Adaptation Options for New Culverts [*Continued 1*]

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)
Water Level / Chemistry [Continued 1]	***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[9]	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	Medium	Perching of culvert due to long-term scour will create an aquatic organism passage obstruction	-	-	-

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[9] 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 8: Adaptation Options for New Culverts [*Continued 2*]

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)
Water Level / Chemistry [Continued 2]	***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				

Table 9: 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[10]
			Pipe jack and replace with larger culvert	Moderate	
			Add headwall and end wall[11]	Low to moderate	
			Install roadway overtopping scour protection[12]	Low	
			Install debris guards / racks upstream[13]	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	

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[10] 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.

[11] For cases of pipe projecting from fill

[12] 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.

[13] 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.

Table 9: Adaptation Options for Existing Culverts [*Continued 1*]

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)
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[14]
			Pipe jack and replace with larger culvert	Moderate	
			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 surges14
			Pipe jack and replace with larger culvert	Moderate	

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[14] 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 9: Adaptation Options for Existing Culverts [*Continued 2*]

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)
Water Level / Chemistry [Continued]	***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 Specifications for protective liner / coatings	Add protective liner / coating	Moderate	-
	Ocean acidification				

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 impacted 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 U.S. Army Corps of Engineer's sea level rise policy and how adaptation has been considered in any USACE activities affecting one of its projects. (USACE 2012) 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.

Step 2: Identify the possible climate-impacted design parameters for the given asset type

Step 2 of the analysis identifies the specific climate stressors that the project will likely be subject to. The detailed tables included in this report and in the CD-ROM can assist in this effort. To use them, first identify the asset type(s) relevant to the project: bridges, culverts, storm water infrastructure, slopes/walls, and/or pavement. Next, select the corresponding tab(s) in the Excel file on the project website or on the CD-ROM included with this report.

Within each asset table, the *First-Order Climate Variable* columns (columns B and C) provide a listing of all the possible climate stressors relevant to that asset type. 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). 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*. For example, stream flows for culverts can be estimated using three different techniques: theoretical models, regional regression curves, or stream gage 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 impact the project along with a listing 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*. 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* column) presents 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 intensity-duration-frequency (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 Clasius-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 ensembles 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 end of the asset's design life is advantageous because it provides some insurance in case the, 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 impacted 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 my 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 makes sense. The approach determines how many adaptation options will be developed for the engineering analysis.

One option is a scenarios 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 scenarios 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 EPA's set of water-related tools for doing benefit-cost analysis in the context of climate change. (http://water.epa.gov/type/oceb/cre/toolkit.cfm) The US Army Corps of Engineers recognizes the benefits of a scenarios approach and now requires that for certain Corps activities three sea level rise scenarios be taken into account and design/planning alternatives be created for each of them. These are then evaluated across the range of scenarios using multiple criteria including, optionally, benefit-cost analyses.

Alternately, if an agency has limited resources to engage in scenario analysis and there is a supportive political environment for adaptation, it may choose to forego 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, 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. Nor should this 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 table differentiates the adaptation options by their application to existing or new assets. Guidance on adapting existing assets is presented in columns P-R. Column P, *Retrofit Options*, presents general retrofitting strategies for each climate sensitive design 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 two 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. As their headings imply, these columns provide cost approximations and special considerations for the retrofit option with the corresponding Roman numeral. For example, when considering how to retrofit a culvert that is (or may be) experiencing issues due to higher stream flows, one retrofit option (Option I) entails adding additional culverts. Following the Roman numeral I across columns Q and R, it is shown that this retrofit option has moderate to high costs and special consideration needs to be made for downstream flooding liabilities. The costs for the adaptation options shown throughout the table 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 corresponds to a 1 to 5% addition in total asset cost, medium 6 to 10%, high 10 to 25%, and very high greater than 25%. 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.

Adaptation options for new infrastructure are presented in columns J-O. The *Costs* and *Special Considerations* columns are organized in a similar way to their counterparts in the retrofit options for existing assets described above. The key difference is that for new infrastructure two adaptation options are shown in the table: 1) traditional design options with climate model inputs (columns J-L) and 2) alternative design options (columns M-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. This includes 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 table 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 on 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, one should consider whether parts or all of the alignment may be re-routed to non-flood prone areas. 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 one lessens the exposure of that asset to long-term climate change, and the uncertainty of that change. 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 scenarios-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 scenarios 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 amongst the different project alternatives: whichever alternative has the highest incremental B/C 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) (Federal Highway Administration *Economic Analysis….*). A climate risk adjusted B/C 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 B/C methodology has two primary purposes within the scope of traditional benefit-cost applications:

1) Help agencies weigh potential adaptation strategies in terms of costs and benefits; and

2) 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 B/C 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 B/C methods are already in use.

Summary

To most transportation agencies, the most important concern with climate change adaptation will be answering the question "what do I 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 Tables 7 to 9, 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-impacted design parameters for the given asset type, 3) Review past climate trends and obtain and/or calculate climate projections, 4) Identify the design components impacted by changes in climate, 5) Determine adaptation options, and if desired, 6) Conduct a scenarios driven benefit-cost analysis.

7. Other Agency Functions and Activities

Introduction

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 & 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 10 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 4. 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 object 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) 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.

Table 10: Weather-related Impacts on 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	●	●	●		●	●

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 & 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 both 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 and 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 $2.5B 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 impacted 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 of 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 impacted by high intensity storms
- Increased deployment and use of roadway weather information stations (RWIS) 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
- drought periods or invasive species attack
- 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

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

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
- 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: Gregory C. Johnson, "How Can DOT Operations and Maintenance Prepare for Extreme Weather Events?" Presentation at the Annual Meeting of the American Association of State Highway and Transportation Officials, Pittsburgh, PA, Nov. 17, 2012, Michigan Department of Transportation, Lansing, MI.

Lockwood suggests that changing climatic and weather conditions leads 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 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.

- 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."*(Lockwood 2008)

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 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 adapt 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, the mowing of 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, DC. 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 is especially true for culverts plugged with woody debris – which can be exacerbated by the death of trees caused indirectly by climate change, be it in the form of 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 over committed 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 cost of preventative maintenance and 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 U.S. 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: (Federal Highway Administration 2012b)

> "Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. 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, Rowan, Savonis and Choate 2012)

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
- Lifecycle cost and risk management analysis
- Financial plan
- Investment strategies

Several of these components could relate to climate change-related factors that affect the condition (current or future) of highway assets, e.g., the objectives and measures for asset management, lifecycle 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 11 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 above, one could include risk appraisal into 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 one could envision "smart" sensors 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 that 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 above, 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 11 to serve as a climate change resource to the agency. Having such a system in place is critical if the agency

Table 11: 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	Mapping, potentially using GIS, of infrastructure assets in vulnerable areas; Inventory assets that are susceptible to climate change impacts; Collect elevation info 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, Incorporating risk appraisal into performance modeling and assessment; Identification of high risk areas and highly vulnerable assets; Use of "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; Possible application of 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 into 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; Possible use of climate change-related performance measures; "Triggering" measures used to identify when an asset or asset category have reached some critical level.

Source: (Meyer, Amekudzi and O'Har 2009) decides upon undertaking the threshold policy approach described in the climate adaptation framework.

How Should My Agency Coordinate With Other Organizations and Groups 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 U.S. Army Corps of Engineers).

In addition, one should recognize that 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 continued to rely on their local knowledge and connections to assist VTrans 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 storm-water 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 a handbook on collaboration 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:

- 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 your region or organization (by expanding the constituency base for your 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 forming 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 multi-jurisdictional and multi-agency cooperation.

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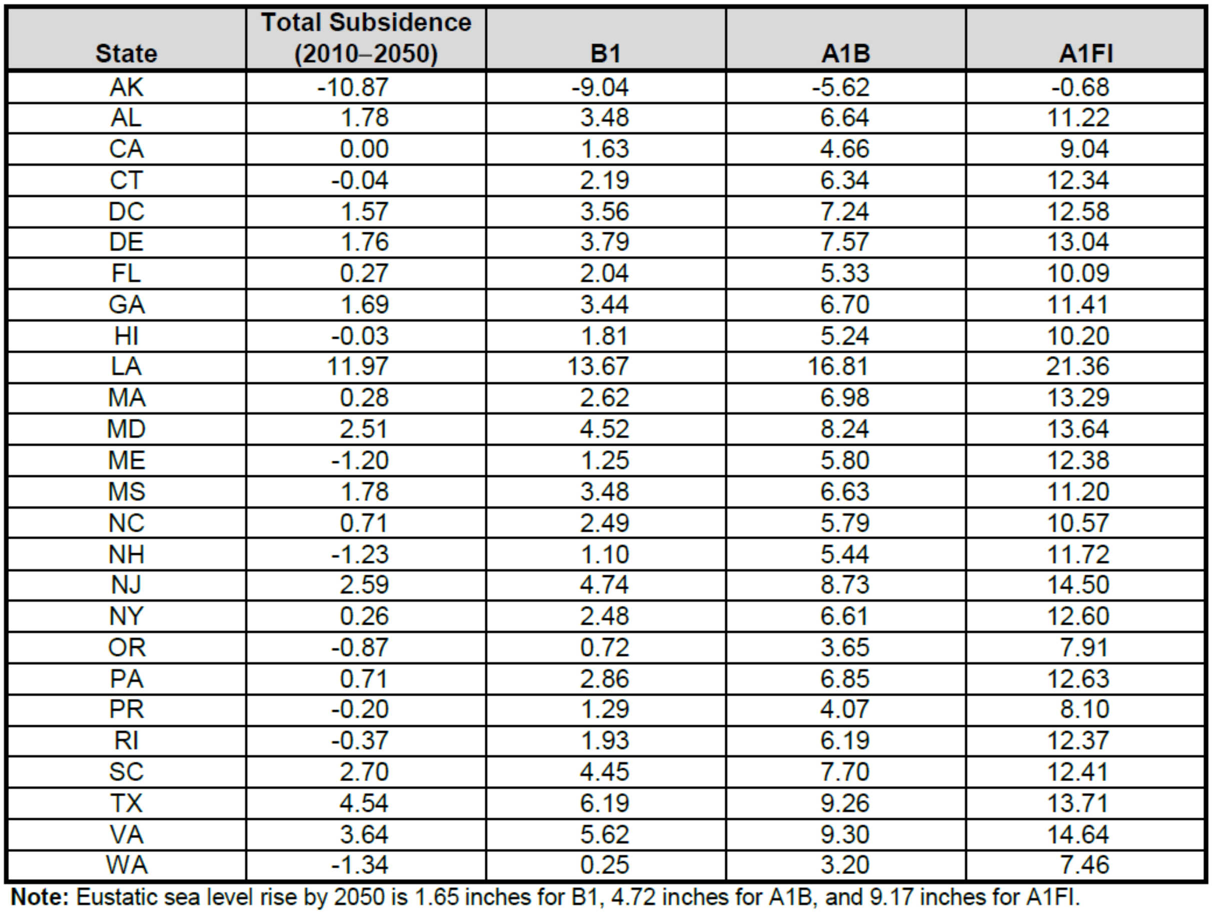
Appendix A: Sea Level Rise Projections

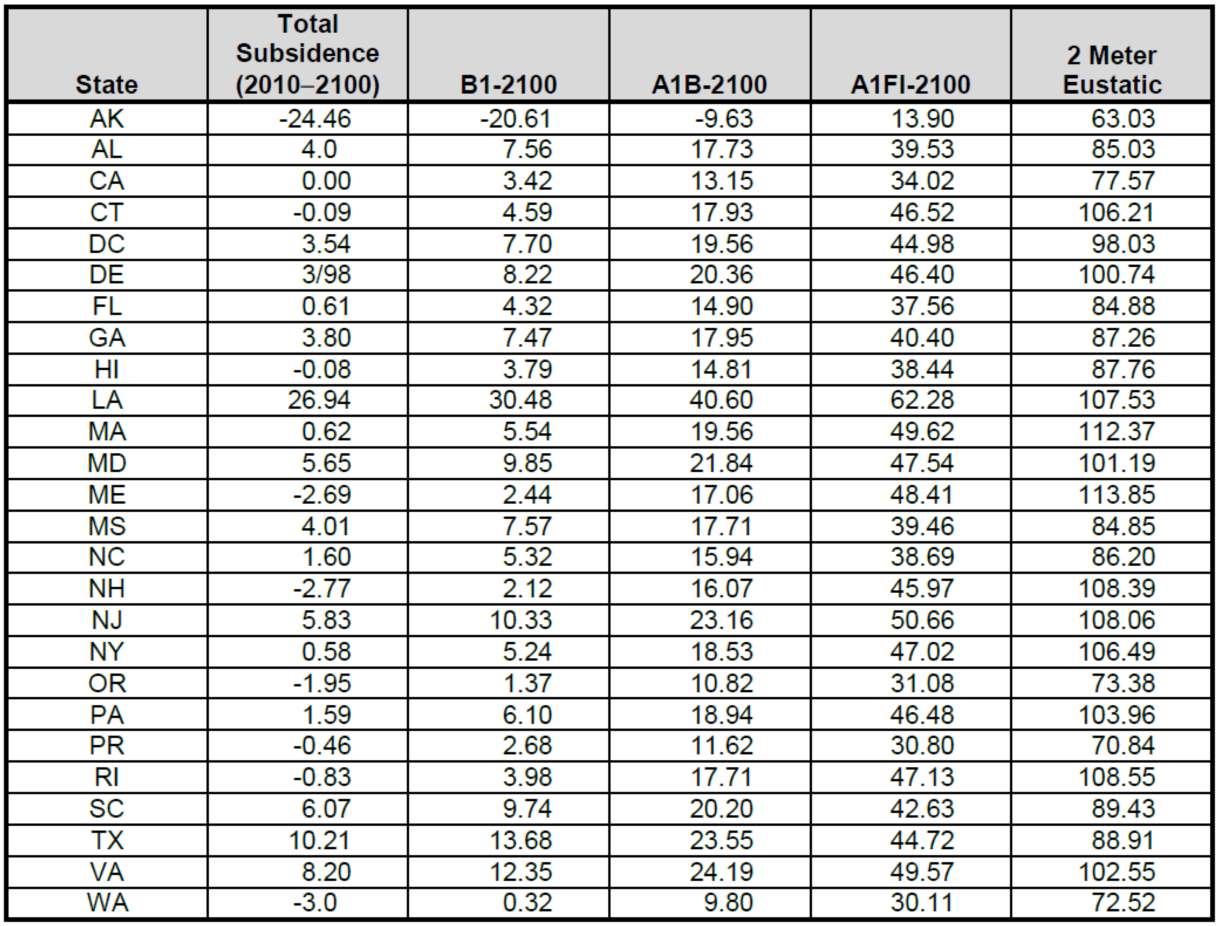
Sea Level Rise by 2050 (relative to 2010) in Inches Taking into Account Subsidence and Uplift



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: Sea Level Rise Projections

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

1) The current asset is in need of imminent replacement or major reconstruction (i.e. is nearing the end of its lifespan). The approach can be used to determine whether the incremental costs of adaptation are economically justifiable.
2) 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 the likelihood of failure given the different designs into the analysis. 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, benefit-cost ratios can be considered in each "out" year in order to guide investment implementation. The adaptation strategy that exhibits negative or very low benefit-cost 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 benefit-cost 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 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 B-1, with further details provided below. 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 benefit/cost calculation represent only the initial cost of a project, and that the change in future agency costs be included in the numerator (Federal Highway Administration *Economic Analysis….*). 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 FHWA *Primer* also recommends estimating all future costs in constant year dollars, without applying an inflation factor.

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

- An adaptation scenario, in which the adaptation strategy is implemented; and
- A no adaptation scenario, in which the adaption 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 historic 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

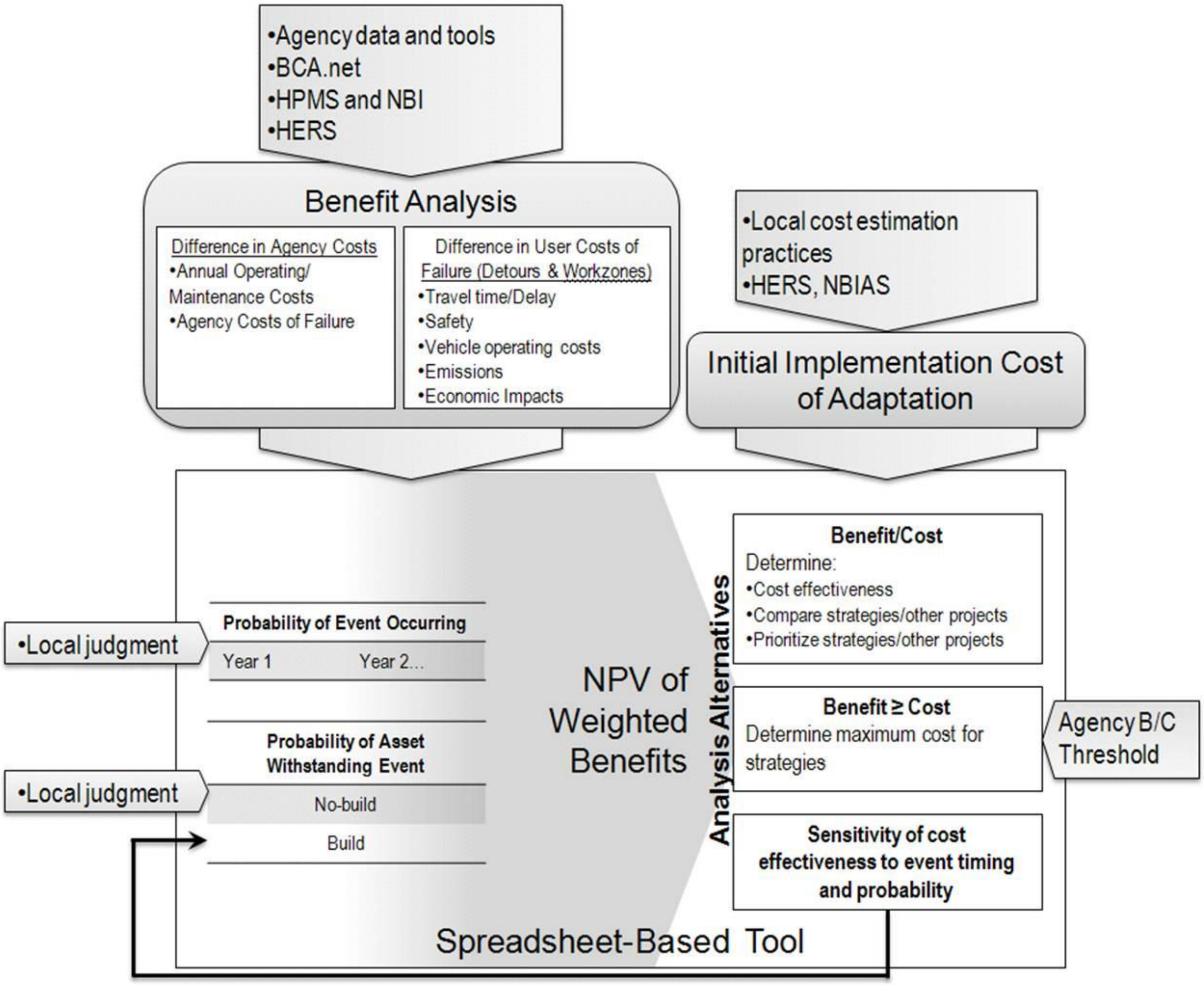


Figure B-1: Climate Risk Adjusted Benefit-Cost Methodology

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 (Meyer, Southworth and Hirshman 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 benefit/cost methodology, the approach can be included in the adaptation benefit-cost analysis. For agencies not currently using benefit/cost analysis, tools such as BCA.net and resources such as the FHWA's *Economic Analysis Primer* can inform the process. Since the details of traditional benefit/cost guidance are addressed in these and other materials, they will not be readdressed as part of this effort.

In traditional cost/benefit 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

$AADT_Y$ = 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 comprised 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% 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 benefit cost 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:

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

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-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} = $UF\ x\ PB_{NAi}$

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

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)

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

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 *equation 1*)

Step 8. Evaluate Results

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

1. Calculate a benefit/cost ratio. Estimate the initial cost of the adaptation strategy and calculate a benefit/cost ratio as follows:

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

where:

BCR = benefit/cost 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 the FHWA *Economic Analysis Primer*)

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 benefit/cost ratio is greater than or equal to 1);
- Compare multiple potential adaptation mitigation strategies (e.g., rank by decreasing benefit/cost ratio); or
- 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 benefit/cost ratio from each potential project as one goes from the lowest to highest cost project).

2. 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.

3. 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 impact 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 above 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 phenomena, 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 above 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 benefit/cost ratios for other potential transportation projects.

Illustrative Example

This section illustrates the application of the process described above, 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. Key assumptions include:

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.

Estimate the 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.

Estimate the 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
- Percent 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 mpg

- 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).

Estimate the 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% of the failure threshold being exceeded from 2010 through 2020. The agency estimates that flows after 2020 will increase by 2% per year from 2020 through 2040, raising the probability of a 100,000 cfs event from 0.2% (500-year) to 1.0% (100-year). The incurred probability of exceedance of the 100,000 cfs event under this scenario increases from 2% during the 2010 decade, to 4% during the 2020 decade, and up to 8% 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% chance of withstanding the event, and that in the adaptation scenario, it would have a 99% chance.

Evaluate results (Step 8). (Steps 6 and 7 involve the mathematical combination of the estimates in Steps 4 and 5 and are therefore not shown in this example.) 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%, the agency calculated a benefit/cost ratio (B/C) 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 was 0.96. This result indicates that although the adaption 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 B/C results into infrastructure decision-making

Generally, benefit cost analysis is intended to support agencies in identifying and valuing the direct and indirect benefits and costs of projects over a multi-year timeframe. 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 benefit cost approaches, climate risk adjusted analyses can provide key inputs into several different transportation decision-making processes, including:

- Long Range Planning: With minor modifications, the benefit/cost methodology can be employed, to help agencies identify the appropriate timeframes 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 a project selection/prioritization process (for creation of the STIP/TIP, 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 MPOs already use economic tools including benefit-cost analysis to help them determine the most beneficial projects by identifying, quantifying, and valuing benefits and costs over a multiyear timeframe. 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.