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ASSESSMENT OF THE BODY OF KNOWLEDGE ON INCORPORATING CLIMATE CHANGE ADAPTATION MEASURES INTO TRANSPORTATION PROJECTS

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Front Matter

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1 Introduction

Transportation systems are vulnerable to extreme weather and climate change impacts, such as increased temperatures, sea level rise, and more intense storms. These events threaten the ability of transportation agencies to effectively plan, invest in, operate, and maintain their infrastructure. Over the past decade, many transportation agencies have transitioned from vulnerability assessment to adaptation planning. Having evaluated the risk that climate change poses, these agencies are ready to begin building their resilience to a range of possible climate futures.

This report highlights adaptation actions that transportation agencies around the world are already pursuing and articulates a growing set of best practices for implementing adaptation. The report also discusses strategies, examples, and best practices for evaluating the costs and benefits of adaptation. The purpose of the report is to provide transportation practitioners with a guide to the current “state of practice” in this field. Since many transit agencies have actively pursued adaptation strategies, this report also covers relevant adaptation initiatives from transit agencies.

The report is organized into seven sections. The first section provides an overview of existing research and literature on adaptation. Each of the nine studies highlighted in this section has contributed significantly to the field transportation adaptation field. Next, the report identifies common adaptation actions occurring in the disciplines of transportation asset management, long range transportation planning, design and construction, operations and maintenance, and emergency management. The fourth section highlights common best practices emerging across these adaptations, such as recognizing adaptation as a co-benefit and tracking data on extreme weather. Next, the report transitions to discussing methods of evaluating costs and benefits of adaptation options. The final sections of the report describe common barriers to adaptation, methods of overcoming those barriers, and ongoing research in the field.

Distinctions between vulnerability assessment and adaptation can be blurry. The two processes often occur in tandem, with vulnerability assessment results directly informing adaptation planning. In addition, the process of conducting a vulnerability assessment, particularly collecting data and engaging stakeholders, can increase preparedness, coordination, and communication—which can lead to adaptation. To the extent possible, this report focuses exclusively on adaptation. In this report, we consider adaptation to be any activity that reduces the vulnerability of transportation systems to future changes in climate. Common examples of adaptation include shoreline protection to reduce exposure to coastal hazards, design updates to reduce sensitivity, and building additional redundancy into the system to increase adaptive capacity.

2 Overview of Research and Literature on Adaptation

Over the last several years, government agencies, academic institutions, and other organizations have conducted substantial research on climate change adaptation within the transportation sector. These documents provide summaries of transportation adaptation initiatives underway in different geographic areas or modal types, summarize lessons learned, and provide suggestions for future activities. These documents can be valuable resources for transportation practitioners wishing to pursue adaptation initiatives. While much additional research still needs to be done, the existing work lays a strong foundation that can benefit future efforts.

Table 1 highlights nine studies that represent strong examples of existing transportation adaptation research. Some of the resources discussed here focus on identifying and evaluating specific adaptation strategies, whereas others focus on organizational *process* and how to mainstream adaptation within existing institutional structures. Most of the resources in Table 1 are influential, national-scale studies; however, the next section of this report identifies specific, local adaptation activities that are underway across the country.

Table 1. Summary of Existing Research on Transportation Climate Change Adaptation

Study	Description
“Adapting Transportation to the Impacts of Climate Change” (TRB 2011)	<ul style="list-style-type: none"> • Comprehensive overview of climate change impacts and adaptation in the transportation sector • Includes an overview of the potential impacts that climate change may have on the transportation system; a review of activities underway at the Federal level in the U.S. and the U.K. that address the challenges of incorporating adaptation into transportation decision making; specific adaptation strategies in U.S. states; and the need for cooperation in adopting adaptation strategies
“Potential Impacts of Climate Change on U.S. Transportation” (TRB 2008)	<ul style="list-style-type: none"> • Provides a detailed review of the impacts climate change will have on the U.S. transportation system • Discusses how climate change adaptation can be incorporated into decision making, the challenges of adaptation planning, and potential adaptation strategies
“Progress and Challenges in Urban Climate Adaptation Planning: Results of a Global Survey” (Carmin et al. 2012)	<ul style="list-style-type: none"> • Survey of 468 cities to gather feedback from a broad and global group • Of the cities surveyed, nearly 68 percent reported some level of adaptation planning. The survey highlighted four adaptation activities that are particularly common among respondents: meeting with local government departments about adaptation; conducting research about adaptation; creating a task force or commission to support adaptation planning; and partnering with

<p><u>“Caltrans Activities to Address Climate Change”</u> (Caltrans 2013)</p>	<p>NGOs and community groups, other cities, and businesses</p> <ul style="list-style-type: none"> • Overview of all climate change activities (including adaptation activities) underway within the agency • Caltrans provides an overview of their adaptation activities, which include developing internal guidance documents to raise awareness about potential climate-related transportation impacts; incorporating design and construction suggestions into their <i>Highway Design Manual</i>; and maintaining and operating vulnerable roadways with the threat of flooding and erosion in mind
<p><u>“Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation”</u> (FTA 2013)</p>	<ul style="list-style-type: none"> • Case study approach to identifying existing transportation adaptation tools and strategies, and discusses modification of such strategies for application in a transit setting • Concludes that there are four overarching categories of adaptation strategies: maintain and manage, strengthen and protect, enhance redundancy, and abandon infrastructure in areas of extreme vulnerability
<p><u>“Climate Change Impacts on Transportation in the Midwest”</u> (Posey 2012)</p>	<ul style="list-style-type: none"> • White paper on transportation adaptation activities underway in the Midwest • Includes several case studies on existing adaptation initiatives underway in Chicago, Wisconsin, and Michigan • Chicago’s transportation adaptation efforts are focused on storm water management • Wisconsin Department of Transportation is evaluating the costs of flood-proofing certain corridors against the costs of temporary closures of those roads • Michigan Department of Transportation is considering a variety of adaptation measures to reduce risks from more intense precipitation and heat events
<p><u>“Promising Practices in Climate Adaptation and Resilience: A Guide for Local Leaders”</u> (ISC 2010)</p>	<ul style="list-style-type: none"> • Guide features case studies of various U.S. cities developing adaptation plans, integrating adaptation into local planning practices, establishing and maintaining a local commitment to adaptation, and successfully collaborating across jurisdictions • Case studies do not focus solely on transportation, but they provide insights into successful practices used for adaptation planning at a local level; many of those practices can be utilized for local transportation planning efforts
<p><u>“Synthesis Report of FLMA Climate Change Efforts”</u> (FHWA 2012a)</p>	<ul style="list-style-type: none"> • Synthesis of best practice adaptation activities underway within Federal Land Management Agencies (FLMA) throughout the U.S. • Shows that of the agencies engaging in adaptation activities. Much of the work referenced in this document relates to assessing impacts and vulnerability, but it also discusses the extent to which adaptation initiatives and costs have been evaluated and

incorporated into national Parks and Refuges.

[“Planning for Systems Management & Operations as part of Climate Change Adaptation”](#) (FHWA 2013b)

- Summarizes potential climate impacts on system management and operations
- Explores options to build climate resilience by increasing capability to manage more frequent and severe climate events and planning for operations in an uncertain future

3 Activities Underway to Mainstream Adaptation

A perception exists that adaptation will require large, expensive projects that transportation agencies must fund in addition to meeting existing service requirements and regulations. In certain cases, adaptation does require large capital investments. However, most adaptation activities currently underway are incremental shifts in decision making and tweaks to best management practices. Mainstreaming consideration of weather and climate data into day-to-day management is a highly successful and low cost way to begin increasing resilience.

Adaptation strategies span a range of options, from data collection and monitoring to project design and investment decisions. Certain high risk contexts may demand a large-scale capital investment solution (such as coastal protection), while other contexts may be best addressed with slight modifications to existing best practices. For example, a transportation agency may choose to maintain culverts more regularly and with a focus on high vulnerability areas, rather than installing larger storm water drainage structures. In certain cases, an agency might even choose to accept periodic failure of an asset due to extreme weather if the consequences of that failure are minimal and easily repaired. Optimal adaptation solutions are diverse and highly dependent on local priorities, asset characteristics, and expected remaining design life.

This section discusses examples of how adaptation is being mainstreamed into existing decision-making processes, including asset management, long-range transportation planning, design and construction, operations and maintenance, and emergency management. For a summary of adaptation activities identified and information about the adaptation activities, please see Table 5 and Table 6 in Appendix A. Note that while this report catalogs a detailed sampling of current and recent

Adaptation to Extreme Weather Events

State Departments of Transportation (DOTs) manage a diversity of extreme weather events every year, including dust storms, blizzards, and hurricanes. In May of 2013, the American Association of State and Highway Officials (AASHTO) convened a national symposium for state DOTs to share experiences with extreme weather and exchange best management practices. Examples of practices recommended by DOTs include:

- More frequent maintenance of culverts to remove debris (MassDOT)
- Slower speeds of salt dispensing trucks to reduce loss of salt prior to snow storms (Michigan DOT)
- Reliance on a variety of communication channels, including social media, to communicate during extreme weather (multiple)
- Real-world training exercises to practice weather-related emergency response (multiple)
- Installation of sensors to monitor extreme weather risk (Colorado DOT, Arizona DOT)
- Developing tracking systems to facilitate quickly meeting FHWA and FEMA emergency reimbursement requirements

adaptation measures, there may be additional adaptation initiatives underway within the United States and abroad.

3.1 Transportation Asset Management

Transportation Asset Management (TAM) is an emerging business strategy for making improved, data-driven investment and maintenance decisions. TAM encourages agencies to specify goals, develop monitoring programs, and track performance over time. TAM systems are invaluable for vulnerability assessments because they often collect, integrate, and manage data (such as asset condition) that can be used to evaluate the vulnerability of assets to climate change. In addition, transportation agencies with strong TAM systems in place are also better able to monitor the effectiveness of adaptation measures (Meyer et al. 2012).

Many of the adaptation strategies identified in this section straddle distinctions between vulnerability assessment and adaptation. Key strategies include:

- Add climate change risk management objectives into an agency's Transportation Asset Management Plan (TAMP). This tactic will help ensure that performance metrics selected and strategies pursued consider climate change. For example, adding a "flag" for climate-sensitive assets in an asset management system that will appear when the asset is up for maintenance, updates, or other investment decisions.
- Collect data on the costs of extreme weather events (both single-time events and ongoing maintenance costs). This data collection will help "make the case" for adaptation actions by ensuring that the costs of extreme weather are included in cost analyses.
- Incorporate risk ratings or vulnerability indicators into the asset management database. For example, information on the location and elevation of all assets might enable agencies to quickly estimate portfolio-level vulnerability and/or understand where to target adaptation actions.

Several transportation agencies are already implementing these tactics. For example, the Metropolitan Atlanta Rapid Transit Authority (MARTA) is incorporating climate change vulnerability into several existing decision-making frameworks. MARTA is adding a field to its Enterprise Asset Management System to track whether assets are sensitive to climate, adding a climate-related objective to its resource allocation decision-making software (which also tracks objectives such as safety and state of good repair), and will incorporate climate impacts in the Asset Management Plan update (FTA 2011).

Washington State Department of Transportation's (WSDOT) Bridge Office is also integrating climate change into their bridge management system, Bridge Engineering Information System (BEIS) (FHWA 2012b). As part of a statewide, multi-modal vulnerability assessment pilot project,

WSDOT combined sea level rise inundation maps with existing information from BEIS on bridge locations, plans, rating reports, and inspection reports to help staff qualitatively rate bridge condition and climate impacts (WSDOT 2011).

In response to major flooding from Hurricane Irene, Vermont Agency of Transportation (VTrans) used its previously compiled culvert inventory to quickly map all damaged locations (FHWA 2012b). Furthermore, VTrans is making improvements to the Vermont On-line Bridge and Culvert Inventory Tool to allow for integration of assessments of culvert and bridge conditions with screening of geomorphic compatibility with channels to help prioritize infrastructure needs (VTrans 2012). This tool will help VTrans effectively target adaptive upgrades to highly vulnerable infrastructure.

The Maryland State Highway Administration (MD SHA) is collecting climate information, such as sea level rise mapping, and integrating all asset information into one GIS-based system to manage for climate change (FHWA 2012c). The MD SHA used 2011 road closure coordinates to map closures by cause, such as high water, debris, winter precipitation, or other type of incident (FHWA 2012d). During Hurricane Sandy, the State Emergency Management Agency used this GIS data layer to identify potential hazards and improve storm response.

3.2 Long-range Transportation Planning

As transportation agencies begin to consider adaptation to future climate (rather than adaptation to existing climate variability), a key step is integrating climate risk into long-range planning. Metropolitan Planning Organizations (MPOs) are required to write metropolitan transportation plans (MTPs) that address long-term and short term transportation strategies for the region over at least a 20 year planning horizon. The Transportation Improvement Program (TIP) is a five-year work plan that includes a list of projects drawn from the MTP that are planned and feasible in the near term for a metropolitan region.

All of the projects included in a region's TIP are encompassed into the State Transportation Improvement Program (STIP), in addition to a project list developed by the state DOT for rural regions not covered by an MPO. Because the planning process is forward thinking, and has implications that stretch decades into the future, integrating consideration of vulnerability and adaptation into long-range transportation plans (LRTPs) is an important strategy for addressing the long term impacts of climate change.

There are not many MPOs or state DOTs using climate change adaptation or vulnerability as a factor in prioritizing transportation projects as part of the project selection process to move projects from the transportation plan into the TIP. The Boston Region MPO is one example of an MPO that incorporates resilience into project selection, giving points for projects that improve the ability to respond to extreme conditions (Boston Region MPO 2013b).

A discussion of adaptation to climate change is beginning to make its way into more and more long-range planning documents. Transportation agencies are increasingly considering the following adaptive tactics:

- Develop exposure and vulnerability metrics, and use these metrics to inform prioritization of planned projects and funding allocations
- Prioritize transportation projects under multiple climate and climate-influenced scenarios to understand the sensitivity of priorities to future conditions

The Boston Region MPO developed an interactive natural hazards mapping tool that links to the MPO's database of TIP projects (Boston Region MPO 2013a, FHWA 2012a). The tool can be used to determine whether proposed projects are located in areas exposed to flooding, storm surge, or sea level rise. Hampton Roads Transportation Planning Organization, the MPO for the Chesapeake, VA, region, released their 2034 LRTP in January 2012. The Plan acknowledges and discusses in detail the affect that sea level rise from climate change will have on the region's transportation infrastructure. Furthermore, the Plan states that "adapting to the impacts of climate change, specifically sea level rise, may in the long run require moving or rebuilding some of the region's roads." However, adaptation is not specified as being a factor that is considered in prioritizing projects. Rhode Island's state LRTP also addresses adaptation to sea level rise. In the Plan's environmental analysis section, there is discussion of the effect that sea level rise will have on the state's transportation system. Within the policies suggested in the environment category, the Plan also suggests that the state acknowledge the threat that sea-level rise poses, and plan infrastructure improvements with that in mind. Within the planning category, one of the strategies for the state is to obtain digital elevation data on sea-level rise and use the data to assess adverse impacts on the state's transportation infrastructure.

The U.S. Forest Service at Olympic National Forest (ONF) evaluated ways to incorporate climate change conditions into the Road Management Strategy (RMS), a tool to compare the risks that a road segment poses to various resources against the criticality of that road. The analysis helps prioritize roads for maintenance, upgrading, and decommissioning (USFS 2011). The Forest Service recognizes that this type of prioritization and planning is crucial because funding allocated for road maintenance is limited.

The Virginia Department of Transportation (VDOT), in partnership with the University of Virginia and the Hampton Roads Planning District Commission, conducted a vulnerability assessment study to analyze how priorities in the Hampton Roads Transportation Planning Organization's LRTP may change under climate change scenarios (VDOT 2012). The project team developed a multi-decision model to rank and reprioritize the LRTP's proposed transportation projects and multi-modal policies based on future climate factors and other non-climate planning considerations.

3.3 Design and Construction

Weather variables, such as temperature and precipitation assumptions, are often inputs into infrastructure design decisions. For example, the design of storm water drainage systems, airport runways, and bridges all reflect standards for coping with rainfall and heat conditions. These designs are based on statistical analysis of historical weather patterns as well as an assessment of risk and cost tradeoffs. Since design metrics are based on the historical climate, they reinforce the concept of “climate stationarity,” or the assumption that the frequency and magnitude of weather patterns will remain unchanged into the future.

Very few agencies in the United States have explicitly required design changes in anticipation of future climate change, but many agencies have retrofitted or rebuilt assets based on recent experiences with extreme weather. A key consideration for most agencies is that upgrading design standards, or building for more extreme events, can increase project costs. In addition, state DOTs do not feel that climate model outputs have sufficiently high resolution or level of certainty to be directly incorporated into designs. However, there are a number of adaptation actions that agencies have taken to increase resilience, even in the face of data gaps and uncertainty:

- Build culverts and bridges to allow for the passage of aquatic organisms and enhance stream connectivity. A co-benefit of these investments is that the larger culverts will prevent catastrophic failures during floods.
- Include a larger “safety margin” when rebuilding infrastructure that has failed repeatedly in the past.
- Ensure that designs use the most up-to-date versions of the NOAA Precipitation Atlas and evaluate the assumptions behind the key metrics. For example, consider whether the design assumptions encompass an adequate historical period and whether that historical period might have been unusually wet or dry.
- Explore “worst case scenarios” and evaluate whether certain pieces of critical infrastructure should be designed for a more severe event.

Agencies around the world are already implementing these tactics in order to increase infrastructure resilience. The California Department of Transportation is beginning to screen proposed roadway structures in the project initiation phase to identify potential sea level rise vulnerabilities and determine the need to incorporate adaptation measures (Caltrans 2013). In the case of the South Coast 101 High Occupancy Vehicle Lane Project, the DOT evaluated sea level rise vulnerabilities in the project’s draft environmental impact report. The project development team identified three locations within the project limits that could be exposed to a 55-inch sea level rise scenario projected for 2100. However, the team determined that

adjustments to the project were not necessary because the design life of the bridges would be exceeded by the year 2100 (i.e., the design life was less than 88 years).

In New England, the Piscataqua Regional Estuary Partnership (PREP) is reaching out to local transportation stakeholders in Maine and New Hampshire to promote culvert and bridge design standards that allow passage of aquatic organisms and stream connectivity, as well as sufficient capacity to prevent catastrophic failures during floods (PREP 2010). PREP used evaluation methods to analyze the roads and culverts affected by changes in rainfall and extreme storm events and prioritize stream crossings for repair or redesign.

After facing severe flooding and stream-related erosion impacts to road infrastructure during Hurricane Irene, the Vermont Agency of Transportation (VTrans) is employing a new approach for considering hydraulic capacity in design (Meyer et al. 2013). VTrans is using hydrologic and hydraulic modeling and slope mapping to incorporate stream and slope stability into road design. Additionally, VTrans has re-designed their approach for repairing slope sections adjacent to rivers. Rather than placing stone to stabilize the slope, engineers are building the slope to match stable channel dimensions.

The Connecticut Department of Transportation (ConnDOT), funded by the FHWA Climate Resilience Pilot Project, is revisiting current hydraulic design standards for bridge and culvert structures. Although Connecticut has experienced impacts to transportation infrastructure from frequent and intense extreme rainfall events in recent years, the current design standards reference rainfall data that have not been updated in decades. ConnDOT is conducting an inland flooding vulnerability assessment that will compare the hydraulic capacity of bridges and culverts using the older rainfall data versus the more recent rainfall data. The project team will make recommendations about whether design standards should be updated.

Iowa DOT is selectively retrofitting overflow bridges in order to account for localized, extreme flooding events. In addition, the DOT is building a new levee to channel flood waters away from the bridge abutments of an important highway bridge in Des Moines, thereby protecting the bridge structure. While the state does not have enough resources to maintain a regular retrofit program, they are upgrading structures opportunistically when possible (Choate et al. 2012).

Outside of the United States, London's major new rail project, Crossrail, has built in adaptation measures intended to help ensure continuity of service within the project's 120-year design life (FTA 2011). Crossrail's design standards are set to withstand a 1-in-200-year flood and include measures ranging from raised entry and egress levels to active flood gates and stop logs. Air conditioning is also built into the design of the project's trains and platforms to cope with projected higher temperatures.

3.4 Operations and Maintenance

Each transportation agency possesses a set of best practices that already improve resilience to climate variability and change. Many of these best practices have evolved as a result of experiences with extreme weather. For example, Alabama DOT switches maintenance crews to earlier start times in the summer when there are more frequent extreme heat events. Michigan DOT has iteratively improved methods for dealing with winter storms, particularly lake effect snow. The agency has invested in tow plow technology, expanded anti-icing efforts prior to expected storms, and increased their salt use efficiency by mixing it with sand and distributing it at a lower speed to reduce bounce and scatter of the salt into ditches. Transportation agencies iteratively improve their management of extreme weather through the development of best practices, thereby increasing their resilience to extreme weather.

In the immediate term, tweaking existing practices can be a low cost, highly certain way of reducing vulnerability to climate change. Some transportation agencies, such as New Jersey DOT, are using debriefs and other strategies to make sure that every extreme weather event is an opportunity for improvement.

Strategies for Effective Implementation: Opportunistic Adaptation and Adaptation as a Co-Benefit

Participants at the 2011-2012 FHWA Adaptation Peer Exchanges found that it is easier to communicate and justify the need for activities and programs in which adaptation is opportunistic, and increased resilience to climate change is just one of several benefits (FHWA 2012a).

Opportunistic adaptation. Transportation agencies often take advantage of key opportunities to build additional resilience into assets or systems. For example, an agency may rebuild a damaged culvert to a larger size in order to increase its capacity to better handle future flood events.

Adaptation as a co-benefit. Some of the most successful examples of adaptation are projects that have reduced climate risk as a co-benefit, rather than as the primary purpose of the project. For example, District 4 of the California Department of Transportation (Caltrans) recently relocated a section of Route 1 in the Devil's Slide region of San Mateo County, which frequently faced closure and repair due to rockslides and land slippage from adjacent steep slopes (Caltrans 2013). The relocation of two tunnels beneath a mountain will have the added benefit of helping to avoid increased erosion, landslides, or flooding that could be caused by climate change.

Transportation agencies are continuously tweaking best management practices to better maintain and operate road systems. These adaptations span a range of activities, including:

- Prioritize maintenance activities that reduce damage during extreme weather events, such as tree trimming and culvert cleaning.
- During very hot days, shift construction and maintenance activities towards cooler times of the day.
- Deploy “quick maintenance” patrols to check for and repair potholes during extremely hot days.
- Plant drought and heat-resistant plant species for erosion control.

Transportation agencies are already implementing these adaptive operations and maintenance tactics. For example, the Southeastern Pennsylvania Transportation Authority (SEPTA) has accelerated their tree trimming program in recent years in response to lessons learned in previous storm events (ICF ongoing).

Transportation agencies are also looking for ways to use operations and maintenance practices to build resilience over the long-term. Michigan DOT is piloting a maintenance decision support system along a major interstate corridor (Meyer et al. 2013). The DOT is also identifying ways to bring roads back to safe operation more quickly after snow storms, such as changing the types of salts used for ice removal. To cope with soil erosion and landslides, Caltrans is installing subsurface drainage facilities, constructing rock buttresses, inserting reinforcement bars to stabilize steep slopes, and planting erosion control grasses (Caltrans 2013).

To better manage the risk of high temperatures, Amtrak will upgrade a section of overhead electrical wire that tends to sag and tighten in variable temperatures (Amtrak 2011). Intermediate support structures for the catenary wires that power a stretch of track between Trenton and New Brunswick, New Jersey, will be installed to shorten the spans between supporting poles. The Amtrak infrastructure upgrade will improve service reliability and increase resiliency to extreme temperatures in the process.

In response to high temperatures, Transport for London painted the tops of bus white in order to reflect heat and help keep the vehicles cool even if air conditioning units on board malfunction. Transport for London also specified that all buses feature upper deck ventilation systems and tinted windows that can open.

3.5 Emergency Management

As extreme weather events increase in magnitude and frequency, transportation agencies are working to become more agile and resilient. Agencies are also learning from recent extreme events and improving protocols in order to restore service more quickly. Such tactics include:

- Develop and regularly update emergency response plans (Meyer et al. 2013)
- Build larger and more flexible monitoring systems to alert transportation agencies of real-time road conditions, develop capacity of transportation operations centers to integrate sophisticated weather data (FHWA 2013b)
- Increase intra and interagency cooperation (FHWA 2013b, Meyer et al. 2013)
- Develop and train rapid mobilization and deployment teams (FHWA 2013b)
- Allow for flexible resource allocations (FHWA 2013b)
- Invest in staff training in advance of extreme weather, including cross training of staff and training for unusual events (FHWA 2013b)
- Mobilize staff and equipment in advance of extreme weather, when possible (FHWA 2013b)
- Communicate with the public about the status of road closures, safety procedures, and other important information (FHWA 2013b, Meyer et al. 2013)

The Metropolitan Transportation Authority (MTA) Hurricane Plan details maintenance operations protocols such as moving equipment (e.g., rail cars and buses) from low-lying areas or vulnerable outdoor tracks; staging recovery equipment such as generators and chainsaws near areas where they would be needed; and clearing catch basins and sewer lines (NYC MTA 2012a).

In response to extreme lake effect snow storms, the Michigan DOT has changed their strategy for operations and management logistics such as the number of employees assigned to weather response, the numbers and start times of shifts, use of temporary winter employees, and the need for staff lodging when the weather is so bad staff members cannot return home after their shift (Meyer et al. 2013).

Communicating with transportation system users is an immediate adaptation measure that can be deployed prior to, during, and after an extreme weather event. Caltrans has been using real-time message signs and portable signs along roads as well as other communications technologies to indicate road closures during extreme events (Caltrans 2013). Similarly, Missouri DOT (MoDOT) uses a wide range of communication channels including cell phones/texting, e-updates, Facebook updates, Twitter, and Sirius Radio to ensure they reach a wide audience (Meyer et al. 2013). Furthermore, MoDOT reaches the target audience of commercial vehicle operators through communications capabilities of other organizations including trucking associations.

Keeping the public aware is particularly important during emergency events. The New York Metropolitan Transportation Authority (MTA) upgraded its communications technology after a heavy rain event forced a temporary shutdown of the New York City subway system and

affected two million transit users. The agency acquired the ability to send out one million simultaneous email alerts, expanded the server capacity of its website, and improved information feeds, public address systems, and information screens that can operate under emergency conditions (FTA 2011).

In order to quickly recover from major flooding damages from Hurricane Irene, VTrans used an incident command system (ICS) decision-making framework to manage a coordinated response among a large number of jurisdictions and functional agencies (Meyer et al. 2013). Incident command centers (ICCs) were established in different regions affected by the storm and received directions regarding priorities from a Unified Command (UC) in the state capital.

4 Best Practices for Mainstreaming Adaptation

The research and experience to date on incorporating climate change adaptation measures into transportation projects reveal several best practices on early steps that agencies can take to adapt to climate changes or prepare themselves to implement adaptation measures. These best practices can apply to all strategies discussed in Section 3, and can prepare agencies to take advantage of opportunities to adapt as they may arise through standard business practices. These early steps include: tracking performance metrics, incorporating climate change considerations in asset management programs, setting up frameworks to enable opportunistic adaptation, developing adaptation priorities, and developing system-wide approaches to adaptation. Each of these steps helps to incorporate climate change into existing decision-making structures and facilitate implementation of adaptation strategies when opportunities present themselves.

4.1 Recognize Adaptation as a Co-Benefit

Many of the adaptation efforts underway in the United States are not explicitly climate change adaptation projects. This is because resiliency is often just one of many benefits of common-sense approaches to managing transportation systems (see “Strategies for Effective Implementation” text box on page 14). Transportation practitioners should acknowledge that adaptation is not usually a stand-alone effort (FHWA 2012b).

4.2 Establish Tracking Systems and Performance Metrics

Understanding the impacts of weather and climate on transportation systems enables agencies to make more informed decisions about infrastructure investments, operations, and maintenance practices. Transportation organizations have found success by tracking metrics such as how often weather-related disruptions occur, the reasons for the disruptions, the costs of the disruptions, and other factors relevant to decision-making. For example, agencies that track which culverts repeatedly flood or how often extreme heat disrupts the system can be better prepared to make adjustments to improve how the system responds to those events.

Asset management programs are common vehicles for such tracking. Maryland State Highway Administration (SHA), Minnesota DOT, MARTA in Atlanta, and SEPTA in Philadelphia provide some examples of organizations that are using their asset management programs to track metrics related to climate change vulnerability and adaptation (FTA 2013, Hill 2013, Springstead 2012, and Zale and Johanson 2012). Organizations may be able to use asset management programs and asset maintenance systems to flag assets that are repeatedly affected by weather events and track the costs of those repeated events.

Emergency management systems, hazard mitigation plans, or environmental management systems are also vehicles for integrating climate change vulnerability into existing processes (FHWA 2012b). For example, LA Metro is integrating climate adaptation into its Environmental Management System and identifying opportunities for adaptation through their existing environmental clearance process (Liban 2012).

4.3 Plan in Advance to Facilitate Opportunistic Adaptation

The most cost-efficient adaptation measures are those completed in the course of business-as-usual maintenance, construction, repair, or replacement projects. In other words, the time when you are already working on your system is an opportunity to make that system more resilient. However, those opportunities can sometimes arise unexpectedly, and a best practice is that organizations be prepared to convert these opportunities into adaptation projects.

One way to do this is by incorporating climate-related considerations into project evaluations. For example, the Boston Region MPO linked their database of TIP projects to hazard maps so they can determine whether proposed projects are located in areas exposed to flooding, storm surge, or sea level rise and make adjustments to those projects as appropriate (Boston Region MPO 2013a). Caltrans has developed guidance for districts on incorporating projected sea level rise into new projects.

Another key way to do this is by having information about climate impacts, costs, and benefits handy at key decision points. This is where metrics tracking and asset management program areas are useful, because if the information is in plain sight alongside all other information that decision makers use when making project decisions, then it can be mainstreamed in common-sense ways, without necessitating official frameworks.

Finally, pre-planning for post-disaster response can also help organizations take advantage of opportunities to increase infrastructure resiliency after extreme events. If extreme events damage infrastructure, the impetus is to replace those assets as quickly as possible and often there is not time or funding available to rebuild assets (or the system) to be more resilient. This challenge is discussed in Section 6 of this report. Organizations can work to overcome this

challenge by establishing plans ahead of time for how rebuilding for resilience can be accomplished expediently after extreme events.

4.4 Develop Priorities

Developing priorities can be a good way to maximize the impact of adaptation planning, especially with limited resources (e.g., funding, staff time, technical capacity). Criticality and vulnerability are two criteria that agencies have used to prioritize adaptation efforts. Criticality represents how important an asset is to the transportation system. Several transportation organizations have completed criticality assessments to help prioritize adaptation. FHWA provides information on these assessments in its “Assessing Criticality in Transportation Adaptation Planning” resource (FHWA 2011).

Another way to develop adaptation priorities is to identify the historical vulnerability of assets or system components to weather events. Historic vulnerability is a valuable starting point for organizations looking to perform an initial assessment of vulnerability. For example, MassDOT did a survey of district staff to identify problem areas with repeat flooding. Several organizations have also completed prospective vulnerability analyses, which take into account projected climate changes and intrinsic characteristics of assets to determine which areas are most vulnerable. From there, organizations can prioritize adaptation strategies for those areas of the system that are most critical and vulnerable.

4.5 Identify Ideal Timeframes for Adaptation

Understanding *when* to adapt is equally as important as selecting a feasible set of adaptation options. Effective adaptation is all about timing. Many agencies have chosen to begin adapting by selecting strategies that are certain to deliver benefits in the short-term regardless of how climate change accelerates in the future. For example, developing a more sophisticated dust storm monitoring system delivered immediate benefits to Arizona DOT, while also laying the groundwork for adaptive management of possible drier conditions in the future.

4.6 Build Capacity, Engage Stakeholders, and Educate the Public

Implementation of any adaptation strategy requires strong leadership and effective stakeholder engagement. Therefore, one of the most important early steps that a transportation agency can take to prepare for climate change is to educate and engage stakeholders both within and outside of the organization (FHWA 2012b). This type of engagement will help garner both public support (to justify use of resources for adaptation) as well as institutional support (to ensure all levels of staff, from the on-the-ground engineers to the top administrators, understand the need for adaptation).

In addition to building capacity within an organization, educating the public about anticipated climate impacts and supporting effective political leadership are two adaptation strategies that

are low-cost with highly certain benefits (ISC 2010). For example, Arizona DOT undertook a major public outreach campaign to educate drivers about the necessity of pulling over during dust storms (Toth 2013). Using tactics such as a haiku contest, engaging videos with clips of the dust storm, and text message alerts, the DOT has worked towards implementing behavior change to improve public safety. While this outreach has obvious short-term benefits, it is also a way of building Arizona's capacity to handle future changes in climate.

4.7 Share Information among Transportation Practitioners

Across all steps of the adaptation process and types of adaptation activities, state and local transportation officials have achieved success by learning from their peers. Formal peer exchanges, informal relationships between individuals in different organizations, and other ways for organizations to share their experiences have immense value in supporting resilient transportation systems. This type of collaboration and information sharing is a best practice for maximizing the success of adaptation efforts.

These peer exchanges do not need to be formal. Further, they can also occur within organizations. For example, Caltrans has identified liaisons in district offices across the state to share information about climate change best practices (Caltrans 2013). Building relationships within the transportation community is a best practice in adaptation, because states can learn from one another beyond the walls of symposium or workshop settings. When states are comfortable reaching out to other states and discussing their shared experiences and lessons learned, everyone can become more resilient.

Workshops, meetings, and peer exchanges are a good tool for assessing the challenges of and recommendations for incorporating adaptation into the transportation decision making process. Such a forum provides transportation practitioners the opportunity to discuss collaborative activities and past experiences. There have been several key transportation adaptation peer exchanges and workshops in the past few years, with key findings of these meetings available in summary reports. For example, FHWA and AASHTO have hosted multiple meetings over the past three years focused on building a community of practice around climate vulnerability assessment and adaptation planning (see FHWA 2012b, Choate et al. 2012, Meyer et al. 2013).

4.8 Consider Systems Holistically

Finally, a key best practice, and one that is particularly important in the early stages of adaptation planning, is that transportation adaptation planning needs to consider transportation systems holistically. The goal of adaptation is to make transportation *systems* and services resilient, not necessarily specific assets. Adapting specific assets that are critical to the functioning of the entire system may be a key part of an adaptation strategy, but adaptation strategies can also include ways to build redundancy in the system and take into

account future demands on the system as well. Further, transportation systems do not operate in isolation, and their vulnerabilities are also closely tied to vulnerabilities in other sectors, such as the energy sector. A best practice in adaptation planning is to consider the system as a whole, as opposed to adapting asset-by-asset.

5 Assessing Costs and Benefits of Adaptive Strategies

Estimates of the costs and benefits of adapting transportation systems to climate change can provide useful input into transportation planning and decision making. At all levels of government, cost estimates can inform understanding of long-term investment needs and support strategic planning. At state and local levels, information on costs and benefits can also facilitate evaluating and choosing among individual adaptive actions/options, or comparing sets of options. Understanding the costs of “no action” can help show when investment in adaptation measures makes financial sense.

In practice, estimating the costs and benefits of adaptive measures can be tricky. Costs of adaptation can be very project- or site-specific. Benefits of adaptation are sometimes associated with a large amount of uncertainty. Although economists have well-developed methodologies for estimating costs and benefits of a variety of actions, cost-benefit analyses are still not always used in developing climate adaptation plans due in part to the challenges of quantifying costs and benefits. However, new methods have recently been tested by some agencies to begin quantifying costs and benefits.

The remainder of this section focuses on these issues from several perspectives, and is organized as follows: (1) an overview of how costs and benefits are defined; (2) a discussion of traditional methods for estimating costs and benefits; (3) example “real-life” efforts to estimate costs and benefits of climate change adaptation in the transportation sector; and (4) best practices moving forward.

5.1 Defining Costs and Benefits of Adaptation

Actions taken to adapt transportation systems to climate change have both costs and benefits. Costs can include increased construction cost associated with designing a bridge to be able to withstand more frequent and intense storms, training costs associated with process or equipment changes, or the increased cost of labor and materials if operation and maintenance activities change or occur more frequently. Costs can also include broader effects (whether positive or negative) on the economy and jobs.

The benefits of adaptation are the adverse impacts that are avoided; the more effective adaptation is, the greater the benefits. Benefits could include savings from avoiding the need to

repair/replace assets. Benefits could also include impacts on quality of life from reduced traffic delays, avoided risks to human safety, avoided disruption of the flow of goods, etc.

5.2 Traditional methods for estimating costs and benefits

Methods to estimate costs and benefits have been widely applied in non-climate contexts, including analyses of regulations promulgated by DOTs and the analysis of specific project investments. In some cases these methods have also been tested or applied to climate adaptation planning, particularly for developing countries (see, for example, World Bank 2010). Thus, some resources exist to assist transportation officials in starting to understand the analytical techniques (see text box below). However, applying these methods to estimate the costs of adapting transportation planning to climate change poses challenges. Estimating costs and benefits using these methods can require extremely detailed information on the timing and level of climate impacts on vulnerable resources, the cost and efficacy of individual adaptation options, and an assessment of the extent to which different adaptation options would be applied. Often, this information is just not available to transportation officials. Thus, the appropriate approach to estimating adaptation costs and benefits, and the manner in which the information is used, will depend both on the resources available to the decision maker and the needs of the adaptation planning process.

Resources and Methods to Estimate Benefits and Costs

The following resources provide transportation officials with a starting point in estimating the costs and benefits of adaptation measures:

[Transportation Research Board Report: Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System](#). The report evaluates methods to measure direct and indirect economic impacts of disruptions to the goods movement system, and develops conceptual methodologies to estimate such impacts. Case studies to illustrate the use of the methodologies at different scales and in different contexts.

[FEMA Benefit-Cost Analysis Tool](#). The tool consists of guidelines, methods and software modules for estimating the benefits and costs of mitigation strategies to a range of major natural hazards, including wildfire, floods, hurricanes, and tornadoes.

[Economics of Climate Adaptation \(ECA\). Shaping Climate-Resilient Development: A Framework for Decision Making](#). This report describes a framework for applying an asset-based Benefit Cost Analysis framework to climate adaptation decision making, and presents case studies applying the framework. The framework identifies steps and challenges in conducting benefit cost analysis for different sectors.

[Guidelines for Preparing Economic Analyses](#). This guidance from the U.S. Environmental Protection Agency discusses a range of practical issues that arise in estimating costs and benefits in a regulatory context, including determining baselines, choosing discount rates, and dealing with benefits that cannot be quantified.

[Economic Analysis Primer](#). This FHWA document is a brief overview of principles, concepts, and methods for performing economic analyses of highway projects.

5.2.1 Estimating costs: Concepts and methods

Adaptation may involve a variety of activities: investment (replacement or new construction), maintenance and repair, relocation or raising structures, building up land, or other physical measures. As part of these activities, adaptation may require training or education and communication. Adaptation often also involves programmatic activities, such as planning, implementation, enforcement, and monitoring. Each of these activities may have associated costs (see “Categories of Costs” text box below).

Researchers refer to a detailed analysis of adaptation costs as a “bottom-up” analysis. Bottom-up analyses are based on detailed, specific information on vulnerable transportation assets, such as inventories of roads and bridges and their susceptibility to climate events, the costs of specific adaptation measures, and an assessment of where, when, and to what extent such measures will be applied. Because this approach requires considerable data on assets and adaptation options, researchers generally conserve resources by developing categories of assets, and applying assumptions about the extent or cost of adaptation to all assets in a category. This type of approach is taken, for example, in a study of the cost of adapting Alaska infrastructure to climate change (Larsen et al. 2008).

An alternative, much less resource-intensive approach is a “top-down” cost analysis, which may be sufficient for many planning purposes. Top down estimates generally use aggregate level data (e.g., total current expenditures, or miles of road) and then make rough assumptions about how those expenditures will change. For example, a study might assume that a fixed incremental percentage over current expenditures/investment will be needed to climate-proof investments, or assume an incremental cost per unit, e.g., per mile of road. Historical data on past expenditures can be used as the basis for developing these assumptions. Top-down studies can then make aggregate statements about adaptation cost needs. This type of approach was adopted in the state level cost estimates prepared for New York State.

While some of the data needed to estimate adaptation costs already exists to support current transportation planning, it is not always readily available for all relevant climate change effects. A recent study gathered information on the maintenance costs that DOTs are experiencing due to recent extreme weather events (Venner and Zamurs 2012). A survey of state DOTs revealed

Categories of Costs

Direct costs are incurred by the entities taking action, and are the most straightforward to identify and measure. Costs that fall into this category include capital costs such as equipment or construction costs, training or education costs, changes in fuel, labor, or other materials. Direct costs may also include programmatic costs or the costs of making institutional or regulatory changes.

Adaptation may result in *indirect* and *hidden* costs, which can be much more difficult to measure. *Indirect* costs include impacts of adaptation on other sectors, or long-term regional or local economic investment and growth (Roson and Tol 2003). Some costs of adaptation may be *hidden*—or not always apparent. For example, land use changes can have implications for habitats, or closing a road for repairs may impede access to important services, such as hospitals.

that data information was often available for flooding and winter storm events, but not from forest fires and wind and dust storms.

5.2.2 Estimating benefits: Concepts and methods

The benefits of adaptive actions are the avoided damages (impacts) of climate change. Impacts of climate change on the transportation sector can be wide ranging. Most immediate are the loss or disruption of transportation services and the impacts on health due to changes in safety and accident rates. In turn, interruptions in transportation services can affect access to critical goods and services such as hospitals, gasoline and food. Impacts can extend to the broader business community and economy, by affecting access of businesses and customers to markets and jobs, to name only a few pathways.

Benefits of adaptation are estimated in several stages. First, estimates of the physical changes in impacts (e.g., delays, fatalities) are developed for a specific climate scenario. Next, the reduction in impacts as a result of the adaptation measure must be estimated, often measured using physical metrics such as length of delay, or numbers of fatalities. Last, economists have methods for translating these metrics into monetary measures, such as the value of lost time (both residential and commercial), increases in vehicle operating costs, estimated medical and other costs of accidents, or the costs of fatalities.

Estimates of the benefits of adaptation measures are even rarer than estimates of the costs. In part, this reflects an initial focus by planning agencies on the very tangible damages to transportation assets and the engineering costs of improving the resilience of these assets, or the costs of repairs and rebuilding. Without quantitative estimates of the broader damages (including impacts to health and safety, quality of life, and similar impacts), it is difficult to determine how adaptation will reduce those damages.

Example Climate-SMART: a Suite of Tools

In partnership with other Canadian government agencies and organizations, the Halifax Regional Municipality is developing a series of tools to support communication impact and adaptation planning (Halifax 2013). The tools include:

- Risk management tool, to help assess vulnerability of physical and environmental assets
- Community-based vulnerability assessment and risk management tool, to evaluate vulnerability for the broader community
- Cost-Benefit assessment tool, to identify and quantify the economic costs and benefits of adaptation measures
- Environmental impact assessment tool, to assess environmental impacts of a project
- Communication and outreach tool, to inform and mobilize vulnerable residents and businesses

At least some of the data to develop impacts estimates already exist at transportation agencies, but may not be generally available or in consistent and comparable forms across agencies. For example, many transportation agencies collect data on streams of services (tons carried or passenger miles traveled), as well as miles of road subject to different types of climate stressors, or the number of delays and cancellations that result from a weather disruption events. SEPTA, for example, has detailed records of the delay minutes and number of cancellations associated with weather events since 2005, which can be used to estimate the potential impacts from an increase in the frequency and/or severity of these events in the future (ICF ongoing).

5.2.3 Putting it together: Benefit- Cost Analysis and other evaluative frameworks

Information on costs and benefits can be integrated in decision making in different ways. The most obvious is to combine them in a benefit-cost analysis, but cost and benefit information can also be used to support decision making as part of a suite of tools (see text box). The types and level of detail of cost and benefit information that is needed will depend on how decisions are made and what framework is typically used. Some approaches to using cost and benefit information include the following.

Benefit cost analysis. Benefit-cost analysis is a process for organizing information on the benefits and costs over time of individual actions, or a set of actions. If benefits exceed costs, then this criterion recommends that an action be adopted (subject to how it fares on other criteria). If benefit-cost analysis is used to compare actions, the criterion says that the action with the highest net benefits is recommended, again, subject to other constraints on the decision and how the actions fare under other criteria. It can also be used to compare portfolios of actions, as well as individual actions.

In the context of climate change, benefit-cost analysis of adaptation options faces several challenges, including data limitations (particularly with regard to quantitative estimates of impacts), the long time frame of the analysis over which climate change, costs, and impacts are difficult to project, and the importance of discount rates in determining the outcome over that long time frame. In addition, while benefit-cost analyses can be conducted when benefits or costs of action are uncertain, the uncertainty of future climate scenarios can make it more difficult to quantify costs and benefits. As part of a suite of tools, however, it can be quite useful, and has been successfully been applied to help rank adaptation options in developing countries by the World Bank, and other organizations (World Bank 2010, Van Logchem and Queface 2012).

Cost-effectiveness analysis. Cost effectiveness analysis compares alternative approaches to meeting a pre-defined goal. For example, where a desired standard of risk can be defined (e.g.,

protection from a flood with a 1% chance of occurrence in a given year), then the criterion favors the policy alternative that meets the chosen standard at the least cost.

Cost-benefit and cost-effectiveness frameworks are most useful for organizing information in circumstances where there is good information on the probabilities associated with different outcomes, costs and goals or benefits are well-quantified, and making a good decision relies on understanding the tradeoffs involved in choosing in different options. These approaches are not always practical, however; at the least, good information on costs, benefits, or on the probabilities of different outcomes—which is necessary to apply the above approaches—may simply not be available.

Alternatives for weighing multiple criteria. There are a number of alternative frameworks that provide ways to rank or choose among alternatives based on multiple criteria. Many of these alternatives involve decision algorithms that have been developed into decision software. In addition to more formal decision analysis tools, simple weighted matrix approaches can be used to compare and assess alternate options.

In some cases, options to deal with climate change cannot be separated and analyzed as distinct within the decision-making process; for example, if a new road is sited so that it will not be vulnerable to expected increases in flooding, it is difficult to analyze the costs and benefits of the climate adaptation portions of the project separate from other aspects. In other cases, decision makers may face non-climate goals or institutional constraints on the decisions they can make, so that approaches that balance costs with other criteria (e.g., service, safety, environmental goals) are impractical.

Despite their limitations in some circumstances, these frameworks have value for organizing and presenting information to decisions makers. Ultimately, how climate change adaptation can be incorporated into decision-making processes, and the information that will be needed to do so, will depend on the nature of the decision, current decision making processes, viewpoints and technical capacity of decision makers, and institutional and legal constraints on the process.

5.3 Example Efforts to Estimate the Costs and Benefits of Adaptation

Regions, states, and municipalities are beginning to build on the results of vulnerability assessments and take steps to develop adaptation plans to reduce climate impacts. These plans sometimes include estimates of the cost of the plan or explicit estimates of effectiveness or benefits. This section presents an overview of recent efforts by government agencies to evaluate costs and benefits of adaptation.

5.3.1 State, Regional, and Local Estimates of Adaptation Costs and Benefits

When developing climate adaptation plans, some states have undertaken detailed vulnerability assessments and analyses of potential adaptation options. In some cases, adaptation cost information has contributed or been used in support of the development of these plans. In rare cases, measures of benefits have also been developed, and used to construct a measure of cost-effectiveness or to conduct a cost-benefit assessment. For the most part, however, information on costs and benefits has not played a large role in the supporting evidence presented publicly as part of state adaptation plans.

New York State, for example, incorporated information on estimated economic impacts and adaptation costs into the development of its statewide strategy to adapt and respond to climate change (NYSERDA 2011). This study uses available evidence to estimate costs, and then applies a benefit-to-cost ratio derived from empirical data from the past 20 years to estimate the likely benefits of adaptation measures.

Where specific investments or other project-level adaptation decisions are under consideration, and would need either to be financed from local budgets or by grants or other financing, cost-level data is more likely to be reported, as well as to be part of the planning process. For example, cost estimates are often available for a variety of state and local projects that represent climate change adaptation, such as projects to replace sea walls to protect downtown areas, to raise and replace transportation infrastructure, or other actions (Sussman et al. 2013).

5.3.2 The Use of Anecdotal or Historical Evidence

States and localities sometimes employ anecdotal or historical information to make a case for the importance of adaptation, or to suggest the potential magnitude of future adaptation costs. For example, cost estimates at the regional and local levels are available for individual events, such as hurricanes or floods; For example, the New York City Metropolitan Transportation Authority (MTA) reports that it will cost \$4.7 billion for the repair and restoration of MTA assets damaged by Hurricane Sandy in October 2012. This is the level of investment necessary to bring facilities and equipment to pre-storm conditions (NYC MTA 2012b). The Vermont Agency of Transportation reports that it will cost \$250-300 million to repair the damage to the state transportation system caused by catastrophic flash flooding from Tropical Storm Irene (VTrans 2012).

In some cases, historical estimates have been roughly extrapolated to suggest future costs of climate change. The Southeastern Pennsylvania Transportation Authority (SEPTA) used reimbursement information submitted to FEMA to estimate the cost of a tropical storm or winter snowstorm (Table 3) (ICF ongoing). SEPTA also used weekly labor costs coded as “weather-related” to estimate the agency’s labor costs associated with major historical weather

events. These costs were then combined with projected changes in the frequency of extreme events (excluding tropical storms)¹ to estimate labor costs in the future. The Chicago Transit Authority (CTA) used a similar approach of collecting information from FEMA claims to assess the costs of heavy precipitation events (Table 4). CTA is also using data from the traction power system (the electricity grid that supplies electrified rail networks) to estimate the increase in electricity use due to extreme heat and associated costs (Peet 2012).

Table 2: SEPTA reimbursement submittals to FEMA for key weather events (ICF ongoing)

Event	Date	Reimbursement total
Hurricane Floyd	Sept. 16-17, 1999	\$1,523,196
Tropical Storm Allison	June 16-17, 2001	\$5,755,364
Winter Snowstorm	Feb. 5-10, 2010	\$1,274,940
Hurricane Irene	Aug. 26-39, 2011	\$2,531,683
Tropical Storm Lee	Sept. 3, 2011	\$4,235,009
Five Event Total		\$15,320,191
Average Cost of Tropical Storm/Hurricane		\$3,511,313

Table 3: CTA costs of selected extreme precipitation events (Peet 2012)

Event	Date	Cost
Flood	Sept. 5-15, 2008	\$3,058,145
Blizzard	Jan. 31-Feb. 1, 2011	\$670,610
Heavy Rainstorm	Aug. 23-24, 2007	\$50,207

Anecdotal information can also provide insight into the potential benefits of adaptation, to the extent that damages from climate events are partially reduced by adaptation. For example, the Washington State DOT assessed economic losses from the closures of highways I-5 and I-90 due to winter storms in 2007-2008. The study surveyed trucking firms and freight-dependent

¹ Changes in the frequency and intensity of tropical storms that will affect Philadelphia are not well known.

businesses to estimate the direct business losses from the road closures (including losses in business sales, additional freight costs associated with delays or detours, and future disruption prevention costs). It then used an economic model to estimate the indirect and induced economic impacts (such as impacts on employment and state tax receipts). The combined costs amount to approximately \$75 million, \$37 million of which is direct business losses (TRB 2012). Such damage/loss estimates provide a baseline against which the benefits of adaptation can begin to be assessed.

5.3.3 National level estimates of adaptation costs

At the national scale, only two studies have attempted to quantify adaptation costs in the transportation sector: one study estimates the cost of strengthening bridges vulnerable to climate change, and the other study estimates the cost of maintenance and design changes to maintain the current level of road service. A summary of these estimates is provided in Table 4. These studies suggest that the total cost of adapting roads and bridges could range between about \$3 billion and \$5 billion annually for the United States as a whole. Neither study estimates benefits of adaptation; both assume that the adaptation measures employed would maintain the current level of infrastructure quality and service.²

Table 4: Summary of adaptation cost estimates in US\$2010 (Sussman et al. 2013)

Study	Adaptation options	Coverage	Adaptation cost estimates
Wright et al. (2012)	Strengthening vulnerable bridges	Continental U.S.	From 2010 to 2090, cumulative (undiscounted) costs of proactive adaptation range from \$141,200 million to \$196,900 million
Chinowsky et al. (n.d.)	Maintenance and design changes for paved and unpaved roads	Continental U.S.	In 2050, annual adaptation Cost (undiscounted) for paved and unpaved roads combined could range from \$1.6 billion to \$2.5 billion

While these two studies have made great strides in expanding our understanding of adaptation costs in the road transportation sector, they present only part of the puzzle. The two studies only examine a subset of possible climate effects, and are limited in terms of the impact

² Chinowsky et al. (n.d.) do not have unit-level cost data that could be used for state and local adaptation estimates. Wright et al. (2012) do not present unit-level cost data in their paper, but indicate that they used published cost data for constructing either a riprap or strengthening piers or abutments that are representative for the industry.

categories, adaptation options, and cost categories that they cover. Consequently, adaptation costs could be substantially higher than those reported in these studies. For example, the study of bridges examines increased river flooding and omits other climate effects, such as extreme heat or heavy wind. The two studies also focus on the direct costs of adaptation (capital and operating and maintenance costs), while leaving out less tangible costs such as those associated with the implementation of adaptation measures (e.g., training). On the other hand, both studies focus on a subset of engineering solutions and do not consider adaptation measures such as process changes; to the extent that alternative adaptation options may have lower costs, the studies may overestimate adaptation costs.

5.4 Best Practices for Evaluating Costs and Benefits of Adaptation Actions

This section describes some of the best practices that are emerging across agency efforts to evaluate the costs and benefits of adaptation actions.

5.4.1 Develop an Information Base

Adaptation options range from system-wide to asset-specific, from infrastructure-based to operations, from construction to planning, and more. Given the potential usefulness of benefit and cost data, but the lack of underlying data, an important first step is to develop an information base while at the same time determining decision maker needs for information on cost and benefits of adaptation, and useful forms of decision support.

5.4.2 Improve Access to Existing Data

Historical data on costs and effectiveness of asset repair and replacement and responses to past weather events can provide an indication of future costs. In addition, routine data collected on traffic delays, fatalities, and other measures of transportation services can provide the basis for understanding impacts of extreme events and other trends in impacts. These data can be collected (in many cases state DOTs already do) and used more widely to develop cost and effectiveness estimates for certain types of adaptation options.

5.4.3 Monitor the Costs of Extreme Weather and Document Damages

Transportation agencies are increasingly tracking data on the costs of extreme weather events; in part because understanding these costs is a prerequisite to identifying where larger-scale, higher cost adaptation interventions may be needed, and in part because better data can support estimates of funding or reimbursement needs. Setting up monitoring systems and methods of tracking costs in advance will prepare agencies to make the business case for adaptation in the future. For example, MassDOT is working with maintenance staff to document information on the drainage impacts of heavy rain and storm events in their asset management system, Maximo. As a second example, Iowa DOT has developed a streamlined reimbursement process to help quickly process funding requests following extreme weather events (Choate et al. 2012).

5.4.4 Characterize Decision Making Processes and the Usefulness of Decision Tools

Adaptation options can be evaluated against many criteria, including: feasibility, efficacy, ability to withstand a range of climate stressors, costs, benefits, fit within existing processes, and alignment with other organizational goals. The integration of climate adaptation options into existing transportation plans should recognize whether—and how—these criteria are balanced and the processes by which planning already occurs.

5.4.5 Stakeholder Engagement

Input from those individuals responsible for implementation is a key component of the evaluation process. On-the-ground practitioners know the systems better than anyone, and often have valuable insights on what strategies may work well and which would be more difficult to adopt. Vulnerability assessment efforts in the past (e.g., MassDOT, SEPTA, Caltrans, Oregon DOT, and WSDOT) have successfully solicited input from staff through meetings, interviews, or surveys. Transportation agencies may choose to use a similar approach to evaluate the feasibility, cost, and efficacy of different adaptation strategies under consideration. For example, the Federal Land Management Agency climate change transportation toolbox developed for Southeast region of the United States includes activities for Parks and Refuges to use in a workshop setting to qualitatively evaluate the costs and benefits of adaptation options.

6 Overcoming Barriers

Approaches for evaluating and implementing adaptation options have been rapidly evolving over the past few years and those at the vanguard have learned valuable lessons. Many transportation officials agree that they should consider climate change in their transportation processes, but still struggle with what concrete actions they should take and how to find and deploy the necessary resources. This section discusses some of the key challenges in implementing adaptation in the transportation sector and provides examples of strategies to overcome these barriers.

Resource constraints. Agencies are dealing with limited financial and human resources, including assets that are well beyond their anticipated useful life. A challenge to adaptation is the need to balance long-term resilience with more urgent requirements to meet acceptable levels of service. To achieve this, adaptation should not be considered a new and separate issue, but should be integrated into existing decision-making processes. Transportation officials can incorporate climate change considerations into the maintenance, upgrading, and expansion of assets as part of the asset management process. Emergency preparedness, post-disaster reconstruction, and long-range planning are additional venues to mainstream adaptation into decision making. Recognizing that there are multiple avenues for adaptation, FHWA released

guidance on the eligibility of adaptation activities for funding under the Federal-aid and Federal Lands programs (FHWA 2012e). FHWA funds are applicable for adaptation across all stages, including the project planning, preventive maintenance, infrastructure preservation, and construction phases.

Another strategy is to implement adaptation as a co-benefit, rather than as an action in itself. For instance, Washington State DOT is installing bigger culverts to improve fish passage, which will also increase the system's capacity to handle future increased stream flows as a result of climate change (FHWA 2012b).

Regulatory or programmatic roadblocks to modifying guidelines and practices to mitigate risk. Some policies may not support or may even discourage rebuilding to projected conditions rather than historically observed conditions. Some examples of specific regulatory or programmatic issues include:

- FEMA flood plain maps and AASHTO design standards do not account for future climate.
- Disaster recovery assistance rules (e.g., Stafford Act, Emergency Relief for Federally Owned Roads (ERFO)) can provide disincentives to adapt. Funding is often made available to rebuild assets to their previous specifications, but may not support rebuilding assets to a design that incorporates expected climate conditions.
- Engineers design to pre-established hydrometeorological benchmarks, and it is not often clear how to incorporate the range of uncertainty associated with climate change projections.
- Resources are limited, and there may not be political support to prioritize adaptation over other projects.

However, there has been recent regulatory development that can present opportunities to overcome these barriers. For example, while climate change is not currently a required consideration in transportation planning under Title 23 of the United States Code, in 2010, the Council on Environmental Quality issued draft guidance on addressing the effects of climate change under NEPA (Sutley 2010). If adaptation has to be considered as part of NEPA in the future, such guidance can help overcome the challenge of lack of political support.

At the local level, another programmatic barrier is the development of hazard mitigation planning separately from local planning processes. This leads to land use and transportation planning that inadvertently encourages development in risky areas. Communities are increasingly addressing this by incorporating hazard mitigation planning into local planning. For example, Chittenden County MPO in Vermont is working with the Department of Housing and Development to integrate climate change adaptation, hazard mitigation, and transportation into a single framework (FHWA 2012b). During FHWA's Midwest Transportation Adaptation

Peer Exchange in 2011, participants agreed that county hazard mitigation plans provide a natural vehicle for climate change adaptation (FHWA 2012b).

Information availability and applicability to local decision making. The amount of projected climate data available can be overwhelming, making it difficult for transportation officials to determine which climate scenarios, models, and data to use for assessing vulnerability and adaptation options. Furthermore, climate projections are often not presented on the same scale as decisions are made, and it can be hard to translate projected regional climate changes into effects on specific transportation assets. State and federal resources can help overcome this barrier. Information on climate change projections and impacts is available from state climatologists or federal agencies including NOAA³ and the United States Global Change Research Program (USGCRP).⁴ FHWA has also published information on regional climate effects, focusing on transportation agencies (FHWA 2010).

State and federal policy drivers are another way of reducing this barrier. These high-level drivers are important both because they provide justification and impetus for incorporating adaptation into existing agency priorities, and because they help mobilize resources for resource-constrained local agencies. For example, Washington State has required all government agencies to use climate data from the University of Washington's Climate Impacts Group, thereby simplifying the process of selecting data sources. In California, Caltrans has issued "*Guidance on Incorporating Sea Level Rise*" (Caltrans 2011) to help internal staff working at the project and planning level determine whether and how to incorporate sea level rise concerns into their projects (FHWA 2012b).

A related barrier is that many transportation infrastructure engineering decisions are based on metrics such as peak flow, water volume and velocity, or intensity-frequency-duration curves for precipitation. These metrics would be affected by changes in rainfall patterns, but cannot be easily related to climate data about 24-hour precipitation. Determining how to translate climate model outputs into useful terms for engineers, particularly in the area of hydrology, is an ongoing area of research (Meyer et al. 2013).

Stakeholder engagement. Lack of coordination and information sharing among stakeholders can hinder the implementation of adaptation. If the public or target audience does not understand the importance of adaptation, they may be resistant to resources being spent on adaptation. It is therefore critical to engage stakeholders, both inside and outside the transportation agencies, in adaptation planning processes. Oregon and Washington DOTs, for

³ See www.climate.gov.

⁴ See www.globalchange.gov.

example, started their vulnerability assessment by interviewing on-the-ground personnel. They also conducted workshops with internal staff to collect institutional knowledge as well as fostering ownership of the assessment results across the entire agencies. In addition, where there is difficulty in communicating the need for adaptation due to the politicized nature of the term “climate change”, agencies have used other phrases such as “extreme events”, “event management”, “multi-hazard management”, and “building resilience” (FHWA 2012b).

Interdependencies of transportation and other sectors (e.g., health and human services, power, telecom, disaster response). Transportation systems do not operate in isolation and some of the most critical impacts will most effectively be addressed by considering the interdependencies and engaging other sectors in developing solutions. As a result, transportation agencies need to work with other departments to develop holistic approaches for addressing vulnerability and building resilience. For example, North Carolina formed an Interagency Leadership Team in 2004 that includes 11 state and federal agencies⁵ to develop sustainable future transportation projects. These agencies were included as they are integrally involved in the state’s transportation planning and development (NCILT 2013a). Since then, the Team has moved beyond transportation and led the effort to understand climate change vulnerability and analyze adaptation options across all sectors. It recently released a study entitled “*Climate Ready North Carolina: Building a Resilient Future*”, which identifies potential climate change impacts and adaptation measures as well as examining strategies for multiple government agencies to work together in a coordinated adaptation framework (NCILT 2013b).

7 Adaptation Research Underway

The state of the practice in transportation adaptation is continuously advancing. At the time of this report, additional research is underway, the products of which can inform how transportation decision makers plan to increase resilience.

The U.S. Department of Transportation (U.S. DOT) is funding adaptation pilot projects to help advance the state of adaptation practice. These pilots are important on several fronts. First, they are helping to increase the number of state and local agencies that are implementing on-the-ground adaptation measures. Second, they help mobilize resources for resource-constrained state and local agencies that otherwise would not have received support for adaptation projects. Finally, they offer important information-sharing opportunities among peer agencies, allowing them to share and build upon each other’s lessons learned.

⁵ The six state agencies are North Carolina Department of Transportation, Environment and Natural Resources, Agriculture and Consumer Services, Commerce, Cultural Resources, and Wildlife Resources Commission; the five federal agencies are Army Corps of Engineers, Federal Highway Administration, Fish and Wildlife Service, Environmental Protection Agency, and National Marine Fisheries Service.

FHWA is funding a series of highway adaptation pilots (for which this report is being developed as a resource). The first round of five pilot projects⁶, conducted in 2010-2011, tested FHWA's climate change vulnerability assessment conceptual model. A second round currently underway includes both pilots focused on vulnerability assessments, and pilots focused on analyzing adaptation options. The 19 pilot teams will share with each other their experiences and lessons learned throughout the process.⁷ The pilot projects are expected to be completed in 2014.

The experiences of these pilot projects will inform updates to FHWA's *Climate Change and Extreme Weather Vulnerability Assessment Framework*. The Framework guides transportation agencies through the process of conducting a vulnerability assessment and processing the results (FHWA 2012c). The Framework discusses ways to incorporate vulnerability into decision making, which include identifying, analyzing, and prioritizing adaptation options; incorporating assessment findings into transportation programs; and engaging stakeholders both within and outside the agency.

The Federal Transit Administration (FTA) is also sponsoring a related series of adaptation pilots, focused on transit. As one of the largest transit adaptation grant opportunities to date, the FTA Climate Change Adaptation Assessment Pilot program is funding seven pilot projects to evaluate climate system vulnerabilities to climate change and opportunities for adapting to the identified climate risks. Through these pilots, feasible immediate adaptation efforts have been identified, including improvement on data collection and strategies for managing right-of-way flooding.

Several California municipalities are addressing climate change impacts in their local Climate Action Plans. Transportation is one of the sectors being considered in many of these adaptation plans. Most of these plans are forthcoming; when they are available, they will provide insight into how local municipalities are planning on preparing their transportation

⁶ Virginia DOT/Hampton Roads, North Jersey Transportation Planning Authority, OahuMPO, San Francisco Metropolitan Transportation Commission, and WSDOT.

⁷ Tennessee Department of Transportation (TDOT), Michigan Department of Transportation (MDOT), Capital Area Metropolitan Planning Organization (CAMPO), North Central Texas Council of Governments (NCTCOG), Maine Department of Transportation (Maine DOT), Arizona Department of Transportation (ADOT), Alaska Department of Transportation & Public Facilities (ADOT&PF) and Alaska Federal Land Management Agencies (FLMAs), Connecticut Department of Transportation (ConnDOT), Massachusetts Department of Transportation (MassDOT), Minnesota Department of Transportation (MNDOT), New York State Department of Transportation (NYSDOT), Metropolitan Transportation Commission (MTC), Broward Metropolitan Planning Organization, Oregon Department of Transportation (ODOT), California Department of Transportation (Caltrans), Hillsborough Metropolitan Planning Organization (Hillsborough MPO), Washington State Department of Transportation (WSDOT), Iowa Department of Transportation (IDOT), Maryland State Highway Administration (SHA)

networks for the impacts of climate change. Sonoma County and Marin County are two of the municipalities currently considering adaptation strategies in their local Climate Action Plans.

8 Adaptation Guidance and Resources

The National Cooperative Highway Research Program (NCHRP) is in the process of developing a guide that presents a diagnostic framework for undertaking an adaptation assessment (NCHRP ongoing). The guide provides information to help transportation practitioners assess the potential climate impacts facing their highway system, consider various adaptation strategies, and incorporate adaptation into the transportation planning process. The final products will include a practitioner's guide, a supporting software tool, and a project final report.

TRB is expected to soon release Synthesis 20-05/Topic 44-08, "Response to Extreme Weather Impacts on Transportation Systems," expected to become the precursor for a database for supporting adaptation planning (TRB ongoing). The study will review eight to ten case studies of extreme events on transportation systems to document preparedness, impacts, response and recovery, fiscal implications, lessons learned, and research needs.

National Center for Freight & Infrastructure Research and Education is conducting a DOT-funded project to develop a method to prioritize critical highway infrastructure by taking into consideration the risks associated with future flooding events (CFIRE ongoing). In particular, the methodology is expected to estimate the actual transportation infrastructure cost of flooding events and evaluate the costs and benefits of potential adaptation strategies.

Other resources look at incorporating adaptation into transportation decision making by investigating what types of strategies are best for various agencies. The National Center for Transit Research (NCTR) is conducting an ongoing study on "Transit Agency Adaptation to Extreme Weather Events" (Welch et al. ongoing). The ongoing study intends to go beyond some of the traditional research that assesses current adaptation activities by attempting to explain why some transit agencies adopt certain strategies while others adopt different strategies. The research will build on existing resources by not only identifying useful transit adaptation strategies, but also providing an approach to assessing various options.

The Vanderbilt Center for Transportation Research (VECTOR) is developing a method to guide transportation adaptation decisions by focusing on a case-study location in the U.S. where a significant weather event has occurred in the recent past (Dobbins and Abkowitz ongoing). After selecting the project site, the study will determine the impacts of the adverse weather event on critical transportation infrastructure in economic, environmental, and social terms. The project will then develop impact thresholds and compile a list of adaptation strategies associated with different degrees of thresholds.

The Oregon Transportation Research and Education Consortium is conducting a literature review, “Assessing Transit Agencies’ Climate Change Adaptation Needs” (OTREC ongoing). This first component of the research will develop a baseline understanding of policy and program responses to climate impacts that public transportation agencies across the nation are taking. The second phase of the project will develop a case study of a public transportation agency in Portland, Oregon, to gain a detailed understanding of adaptation needs.

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10 Appendix A: Detail on Specific Adaptation Initiatives Reviewed for this Report

Table 5. Overview of Adaptation Activities Reviewed

Adaptation Activity	Lead Actors	Timing	Adaptation Strategies				Cost Assessment
			Information Sharing and Training	Management & Planning	Design & Construction	Operations & Maintenance	
State/Local							
Adapting to Climate Change in Olympic NF and National Park	FS, NPS	2008	X	X		X	
Cape Cod Interagency Transportation, Land Use, and Climate Change Pilot Project	FHWA, NPS, FWS	2011	X	X			
North Cascadia Adaptation Partnership (NCAP)	FS, NPS	2011 - present	X	X			
Adaptation Activities at Caltrans	Caltrans	Ongoing		X	X	X	
Adaptation Activities at Southeastern Pennsylvania Transportation Authority (SEPTA)	SEPTA, ICF, DVRPC	2011-present		X		X	
Adaptation Activities at Metropolitan Atlanta Rapid Transit Authority (MARTA)	MARTA, Georgia Tech	2011-present		X			X
Adaptation Activities at Boston Region MPO	Boston MPO	2011-2012		X			
Adapting Vermont's Transportation Infrastructure to the Future Impacts of Climate Change	VTrans	2011 - present	X	X	X	X	

Adaptation Activity	Lead Actors	Timing	Adaptation Strategies				Cost Assessment
			Information Sharing and Training	Management & Planning	Design & Construction	Operations & Maintenance	
Adaptation Activities at Alaska Department of Transportation and Public Facilities (ADOT &PF)	ADOT & PF	Ongoing		X	X	X	
Adaptation Activities at the Metropolitan Transportation Commission (MTC)	MTC	2011-present		X	X		
Adaptation Activities at the Metropolitan Transportation Authority (MTA)	MTA	Ongoing		X		X	
Adaptation Activities at the Washington Department of Transportation (WSDOT)	WSDOT	2011-present			X	X	
Adaptation Activities at the Chicago Transit Authority (CTA)	CTA	2010-present		X			
Adaptation Activities at Maryland State Highway Administration (MD SHA)	MD SHA	Ongoing		X			
Adaptation Activities at Kansas City Area Transportation Authority (KCATA)	KCATA	Ongoing			X		
Adaptation Activities at Hawaii Department of Transportation	Hawaii DOT	Ongoing			X	X	
Adaptation Activities at TriMet	TriMet	Ongoing				X	
Adaptation Activities at Honolulu Authority for Rapid Transportation (HART)	HART	Ongoing				X	

Adaptation Activity	Lead Actors	Timing	Adaptation Strategies				Cost Assessment
			Information Sharing and Training	Management & Planning	Design & Construction	Operations & Maintenance	
Adaptation Activities at Massachusetts Department of Transportation (MassDOT)	MassDOT	Ongoing		X		X	
Adaptation Activities at Michigan Department of Transportation	Michigan DOT	Ongoing				X	
Adaptation Activities at Arizona Department of Transportation	Arizona DOT	Ongoing	X				
Adaptation Activities in Hampton Roads, VA	Virginia DOT, UVA, HRPDC, Hampton Roads TPO	2010-2012		X			
Adaptation Activities at Rhode Island Division of Planning	RI Division of Planning	2012		X			
Adaptation Activities at Missouri Department of Transportation	Missouri DOT	Ongoing	X				
Regional/National							
FLMA Southeast Region Climate Change and Transportation Tool	FHWA, NPS, FWS	2011-present	X	X			
Facilities Adaptation to Climate Change Impacts in Coastal Areas	NPS	2010 - present	X	X			
Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study	DOT	2003 - present	X	X			

Adaptation Activity	Lead Actors	Timing	Adaptation Strategies				Cost Assessment
			Information Sharing and Training	Management & Planning	Design & Construction	Operations & Maintenance	
The Potential Impacts of Climate Change on Transportation	FHWA	2002	X	X			
Amtrak Northeast Corridor Electrical Systems Upgrade	Amtrak	2011-2017				X	
Adaptation Activities at the Piscataqua Regional Estuary Partnership (PREP)	PREP, MaineDOT, NHDOT	Ongoing			X	X	
Adaptation Activities at the Port Authority of NY/NJ	PATH	Ongoing			X	X	
International							
Transport for London: Incorporating Adaptation into Asset Management Systems	Transport for London	2005 - present		X	X	X	X
Adaptation Activities at Tokyo Metro	Tokyo Metro				X	X	
Adaptation Activities in Turkey	Various				X		

Table 6. Detailed Overview of Adaptation Activities Reviewed

Activity	Overview	
State/Local		
Adapting to Climate Change in Olympic National Forest and Olympic National Park	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	Olympic National Forest and Olympic National Park
	Location:	Olympic Peninsula, WA
	Description:	The project conducted a sensitivity assessment of the ONF and identified barriers to management in preparation for climate change. The assessment identified the effects of changes in temperature and precipitation on ecosystem services and species. The project also evaluated management tools and strategies for adaptation through workshops focused on hydrology and roads, vegetation, wildlife, and fisheries.
	Project URL:	http://www.fs.fed.us/ccrc/cases/olympic.shtml
Cape Cod Interagency Transportation, Land Use, and Climate Change Pilot Project	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	Local planning, transportation, and environmental stakeholders in the 15 towns on Cape Cod, and the Cape Cod National Seashore, as well as various federal and regional agencies. Funded by FHWA, NPS, and FWS.
	Location:	Cape Cod, MA
	Description:	The goal of this project was to develop a replicable process for integrating climate change mitigation and adaptation strategies into transportation and land use planning activities. This project utilized CommunityViz, a GIS-based software, to develop and evaluate ten transportation and land-use scenarios. Climate change vulnerabilities were assessed using expert elicitation. A two-day workshop convened stakeholders to evaluate trade-offs among land use, conservation, climate change mitigation, and adaptation. Elements of a refined scenario developed post-workshop were incorporated into the planning efforts and long-range plans of the NPS, Cape Cod Commission, and Commonwealth of Massachusetts.
	Project URL:	http://www.volpe.dot.gov/coi/ppoa/publiclands/projects/interagencypilotproject.html

Activity	Overview	
North Cascadia Adaptation Partnership (NCAP)	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	Two National Parks (Mt. Rainier NP, North Cascades NP), two National Forests (Mt. Baker-Snoqualmie NF, Okanogan-Wenatchee NF), other federal agencies, and local research institutions
	Location:	North Cascades, WA
	Description:	The Partnership between the U.S. FS and NPS aims to assess the vulnerability of cultural and natural resources and incorporate climate change adaptation into land management. NCAP held four two-day workshops in sectors including vegetation and fisheries. Resource specialists from the lead agencies collaborated with scientists to identify key vulnerabilities, determine adaptation strategies, and identify barriers. The scenario planning looked at a range of variables, and focused on hydrological changes for the effort focused on transportation.
Project URL:	http://northcascadia.org/	
Adaptation Activities at Caltrans	Project Type:	Adaptation Strategies
	Participants:	Caltrans
	Location:	CA
	Description:	Caltrans has begun implementing measures to increase resilience across nearly all the agency's functional areas, including planning, project delivery, operations, and maintenance at the headquarter and district levels. At the headquarter level, sea level rise adaptation guidance has been developed in response to a state executive order for coastal projects to consider a range of sea level rise scenarios. Additionally, Caltrans has developed a guidance manual for California MPOs and RTPAs to address climate change adaptation in their regional transportation plans, and features a matrix of potential adaptation responses by climate impact. At the district level, many activities to improve the system more generally have the added benefit of increasing climate resilience.
Project URL:	http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/Caltrans_ClimateChangeRprt-Final_April_2013.pdf	
Adaptation Activities at Southeastern	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	Southeastern Pennsylvania Transportation Authority (SEPTA), Delaware Valley Regional Planning

Activity	Overview	
Pennsylvania Transportation Authority (SEPTA)		Commission (DVRPC), ICF International
	Location:	Philadelphia, PA
	Description:	This project conducted a climate risk assessment and adaptation analysis for a selected regional rail line. The climate hazard of interest was primarily flooding from heavy rain and tropical storms, as well as heat and snow. After an initial literature review, adaptation strategies were assessed and refined through a series of structured conversations with various SEPTA departments. The strategies discussed spanned capital planning, maintenance, and operations. For each strategy, the project team noted how the strategy would fit within existing SEPTA processes and identified major barriers. Adaptation strategies SEPTA is already doing include prioritizing tree trimming year-round and accelerating the activity in advance of big storms; acquiring more back-up power systems; and elevating signal houses in flood-prone areas. Funding for this pilot project was awarded by the FTA and is expected to advance the state of practice for adapting transit systems to the impacts of climate change.
	Project URL:	http://www.fta.dot.gov/documents/APTA - Climate Adaptation - ZaleJohanson - 080712 FINAL.pdf
Adaptation Activities at Metropolitan Atlanta Rapid Transit Authority (MARTA)	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	MARTA, Georgia Tech
	Location:	Atlanta, GA
	Description:	As an FTA Transit Climate Change Adaptation Assessment Pilot Project, MARTA identified climate risks, assessed vulnerability, and developed adaptive management strategies. MARTA assessed initial adaptation strategies based on order of magnitude costs and mapped each strategy to the agency's organizational units. The project focused on identifying opportunities to incorporate climate change considerations in their asset management system to support strategic investment decision-making to respond to climate impacts.
Project URL:	http://www.fta.dot.gov/documents/Springstead MARTA FTA Climate Adaption Pilot 3-20-12_rev4.pdf	
Adaptation Activities at Boston Region	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	Boston Region MPO

Activity	Overview	
MPO	Location:	Boston, MA
	Description:	<p>Boston Region MPO conducted hazard mapping to identify areas where transportation infrastructure and proposed projects may be vulnerable to flooding, storm surge, or sea level rise. The MPO developed an interactive web tool (http://www.ctps.org/map/www/apps/eehmApp/pub_eehm_index.html) that maps the transportation network, natural flood zones, bridge condition, emergency routes, and emergency support facilities. The tool links to the MPO's database of Transportation Improvement Program (TIP) projects and can be used during planning of proposed projects.</p>
	Project URL:	http://www.fhwa.dot.gov/environment/climate_change/adaptation/workshops_and_peer_exchanges/2011-2012_summary/20112012summary.pdf
Adapting Vermont's Transportation Infrastructure to the Future Impacts of Climate Change	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	VTrans
	Location:	VT
	Description:	<p>VTrans is collaborating with several agencies to implement various adaptation and resilience oriented projects. The adaptation actions intend to help improve emergency management of flood risks and include development of flood maps, a state asset system, and a rapid culvert vulnerability tool to inform project prioritization decisions. VTrans is also holding flood resilience training programs for various stakeholders.</p>
	Project URL:	http://vtransplanning.vermont.gov/sites/aot_policy/files/documents/planning/Climate%20Change%20Adaptation%20White%20Paper.pdf
Alaska Department of Transportation and Public Facilities	Project Type:	Adaptation Strategies
	Participants:	Alaska Department of Transportation and Public Facilities
	Location:	AK
	Description:	<p>The Department is largely adapting to a variety of climate impacts including flooding, coastal erosion, and permafrost melt, and intense storms. Actions underway include shoreline protection along</p>

Activity	Overview	
		<p>highways, relocation of an airport, establishing evacuation routes and shelters, drainage improvement, and piloting technology for permafrost protection.</p> <p>Project URL: http://climatechange.transportation.org/pdf/gregovichadot.pdf; http://ine.uaf.edu/autc/projects/preservation-of-the-alaska-highway-phase-2/</p>
Adaptation Activities at the Metropolitan Transportation Commission	<p>Project Type:</p> <p>Participants: MTC</p> <p>Location: San Francisco Bay, CA</p> <p>Description: The MTC participated in FHWA’s Climate Vulnerability and Risk Assessment Pilot program. As a pilot project, MTC conducted a risk assessment with a focus on sea level rise and sketched out a potential adaptation approach. The adaptation process starts out with an initial list of adaptation measures and uses risk profiles and other criteria to narrow down the list to a potential range of near-term and longer term adaptation options. The exercise was carried out for two example assets.</p> <p>Project URL: http://www.mtc.ca.gov/planning/climate/Rising_Tides_Briefing_Book.pdf</p>	<p>Impacts/Vulnerability Assessment, Adaptation Strategies</p>
Adaptation Activities at the Metropolitan Transportation Authority	<p>Project Type:</p> <p>Participants: MTA</p> <p>Location: New York City, NY</p> <p>Description: The MTA conducted a study that identified climate change scenarios and key vulnerabilities of assets and operations using a risk-based approach. While the study produced temporary, mid-, and long-term recommendations, the implementation of several adaptation activities was prompted by the impacts from extreme events including Hurricane Sandy. Efforts to adapt to flooding include elevating grates and raising station entrance platforms.</p> <p>Project URL: http://new.mta.info/news/mta-prepares-hurricane-sandy http://www.mta.info/sustainability/pdf/Jacob_et%20al_MTA_Adaptation_Final_0309.pdf</p>	<p>Impacts/Vulnerability Assessment, Adaptation Strategies</p>
Adaptation Activities at the Washington Department of	<p>Project Type:</p> <p>Participants: WSDOT</p> <p>Location: WA</p>	<p>Impacts/Vulnerability Assessment, Adaptation Strategies</p>

Activity	Overview	
Transportation	Description:	<p>WSDOT participated in FHWA’s Climate Change Vulnerability Assessment Pilot Program and the results from the vulnerability assessment are being considered through several avenues within the department to inform decision-making. WSDOT’s executive management and Sustainable Transportation Team are working to determine possible strategies to reduce risk. Additionally, the department updated guidance for considering climate change impacts at the project-level using findings from the vulnerability analysis. Adaptation measures have been mainstreamed into design and maintenance activities, such as culvert replacement and rock stabilization.</p>
	Project URL:	<p>http://www.wsdot.wa.gov/SustainableTransportation/adapting.htm</p>
Adaptation Activities at the Chicago Transit Authority	Project	Adaptation Strategies
	Type:	
	Participants:	CTA
	Location:	Chicago, IL
	Description:	<p>As a FTA Transit Climate Change Adaptation Assessment Pilot Project, CTA is surveying system vulnerabilities, developing implementation plans for three specific adaptation project areas, and will integrate long-term adaptation strategies into standard practices. CTA has held interviews within the authority to collect information on service disruption, costs, and system vulnerabilities. Additionally, CTA is mainstreaming climate into an asset management approach for bus maintenance facilities.</p>
	Project URL:	<p>http://www.fta.dot.gov/documents/CTA-Climate-Adaptation-Pilot_APTA_Sust_Presentation_2012.pdf</p>
Adaptation Activities at Maryland State Highway Administration	Project	Adaptation Strategies
	Type:	
	Participants:	MD SHA
	Location:	MD
	Description:	<p>MD SHA is using its asset management system as a climate adaptation tool by collecting climate change data, such as sea level rise, to analyze priority assets. MD SHA is integrating the asset and climate data into a GIS-based system. During Hurricane Sandy, the State emergency management agency used a GIS data layer of previous road closures to identify potential hazards and improve storm response.</p>
	Project URL:	<p>http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf</p>
Adaptation Activities at	Project	Adaptation Strategies
	Type:	

Activity	Overview	
Kansas City Area Transportation Authority	Participants:	KCATA
	Location:	Kansas City, MO
	Description:	Kansas City's new bus rapid transit system uses green stormwater infrastructure to prevent localized flooding,
	Project URL:	http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf
Adaptation Activities at Hawaii Department of Transportation	Project Type:	Adaptation Strategies
	Participants:	Hawaii DOT
	Location:	HI
	Description:	Hawaii DOT built retaining wall in an area with repeat landslides.
Project URL:	http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf	
Adaptation Activities at TriMet	Project Type:	Adaptation Strategies
	Participants:	TriMet
	Location:	Portland, OR
	Description:	Portland TriMet installed expansion joints in their rail in response to rising temperatures
Project URL:	http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf	
Adaptation Activities at Honolulu Authority for Rapid Transportation	Project Type:	Adaptation Strategies
	Participants:	HART
	Location:	Honolulu, HI
	Description:	The buses that Honolulu's transit agency uses to evacuate residents to storm shelters are stored at higher grounds. The agency is also pursuing a memorandum of agreement with a nearby military installation to store additional vehicles at the installation when flooding is predicted.
Project URL:	http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf	
Adaptation Activities at Massachusetts	Project Type:	Adaptation Strategies
	Participants:	MassDOT

Activity	Overview	
Department of Transportation	Location:	MA
	Description:	MassDOT frequently removes debris from culverts to minimize flooding impacts. MassDOT is working with maintenance staff to identify and document information on the drainage impacts of heavy rain and storm events in their asset management system, Maximo. MassDOT is assessing adaptation actions for a major expressway in Boston under the 2013-2014 FHWA Climate Resilience Pilot Program.
	Project URL:	http://climatechange.transportation.org/pdf/2013_symposium/6_4_walsh_vulnerability_adaptation_050713.pdf
Adaptation Activities at Michigan Department of Transportation	Project Type:	Adaptation Strategies
	Participants:	Michigan DOT
	Location:	MI
	Description:	The DOT has improved operations and maintenance approaches for dealing with winter storms. Adaptation activities including investing in tow plow technology, expanding anti-icing efforts, and increasing their salt use efficiency. Furthermore, Michigan Department of Transportation is considering a variety of adaptation measures to reduce risks from more intense precipitation and heat events.
	Project URL:	http://glisa.msu.edu/docs/NCA/MTIT_Transportation.pdf
Adaptation Activities at Arizona Department of Transportation	Project Type:	Adaptation Strategies
	Participants:	Arizona DOT
	Location:	AZ
	Description:	In response to dust storms, Arizona DOT developed a dust storm monitoring system and is using overhead message boards, phone systems, and social media to display advisory and warning messages. The DOT conducted a public outreach campaign to educate drivers about what to do during dust storms. Arizona DOT will develop an adaptive design process under the 2013-2014 FHWA Climate Resilience Pilot Program.
	Project URL:	http://climatechange.transportation.org/pdf/2013_symposium/1_5_toth_aashto_extreme_weather_012010.pdf
Adaptation Activities in	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies

Activity	Overview	
Hampton Roads, VA	Participants:	Virginia DOT, University of Virginia (UVA), Hampton Roads Planning District Commission (HRPDC), Hampton Roads TPO
	Location:	Hampton Roads, VA
	Description:	Under the 2010-2011 FHWA Climate Resilience Pilot Program, VDOT conducted a vulnerability assessment study to analyze how climate change may impact the region's LRTP. Soon after, Hampton Roads Transportation Planning Organization released their 2034 LRTP which discusses the effect of sea level rise on the region's transportation infrastructure.
	Project URL:	http://www.virginia.edu/crmes/fhwa_climate/files/finalReport.pdf http://hrtpo.org/page/2034-plan-visualization-tools/
Adaptation Activities at Rhode Island Division of Planning	Project Type:	Adaptation Strategies
	Participants:	Rhode Island Division of Planning
	Location:	RI
	Description:	Rhode Island's state LRTP discusses sea level rise adaptation strategies.
Project URL:	http://www.planning.ri.gov/statewideplanning/transportation/transportation2035.php	
Adaptation Activities at Missouri Department of Transportation	Project Type:	Adaptation Strategies
	Participants:	Missouri DOT
	Location:	MO
	Description:	Missouri DOT uses a wide range of communication channels to notify drivers of extreme weather events.
Project URL:	http://climatechange.transportation.org/pdf/2013_symposium/AASHTO_EWESymposium_2013.pdf	
Regional/ National		
FLMA Southeast Region Climate	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	FHWA, NPS Southeast Region, FWS Southeast Region, Alligator River National Wildlife Refuge, J. N. "Ding" Darling National Wildlife Refuge, Cumberland Gap National Historical Park, Everglades National Park

Activity	Overview	
Change and Transportation Tool	Location:	Southeast US
	Description:	The Federal Highway Administration (FHWA) is partnering with two Federal Lands Management Agencies (FLMAs) in a project titled “Strategic Research Initiative: Integration of Federal Lands Management Agency Transportation Data, Planning, and Practices with Climate Change Scenarios to Develop a Transportation Management Tool.” The project is intended to develop a tool that will help agencies manage their transportation assets in the face of climate changes. The overall project has several components: (1) a synthesis report of FLMA climate change efforts and current best practices, (2) a Southeast Region Climate Change and Transportation Tool that will help Parks and Refuges plan for reducing GHG emissions and climate vulnerabilities of each unit, and (3) best practice workshops at four pilot units (two Parks and two Refuges) to test best practices and tool components.
	Project URL:	NA
Facilities Adaptation to Climate Change Impacts in Coastal Areas	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	NPS, individual parks
	Location:	Various
	Description:	SOCC, in partnership with CCRP, is conducting a two-phase pilot effort called “Facilities Adaptation to Climate Change Impacts in Coastal Areas.” In the first phase, NPS worked with ICF International to develop and apply a high-level risk screening tool to assess risk posed by sea level rise to facilities within coastal parks. In the second phase, NPS is working with ICF International to develop a park-level risk screening approach and with Robert Young at Western Carolina University to further examine the risk of facilities within Phase I parks that could be impacted by a one meter rise in sea level. ICF International is currently working with two pilots: a Pacific West unit (Pu'uhonua o Honaunau National Historical Park in Hawaii) and a Northeast unit (Assateague Island National Seashore in Maryland and Virginia).
	Project URL:	NA
Impacts of Climate Change and Variability on	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	U.S. DOT
	Location:	Gulf Coast Region

Activity	Overview	
Transportation Systems and Infrastructure: Gulf Coast Study	Description:	To better understand potential climate change impacts on transportation infrastructure and identify adaptation strategies, the U.S. Department of Transportation (U.S. DOT) is conducting a comprehensive, multi-phase study of climate change impacts in the Central Gulf Coast region.
	Project URL:	Workshop report available at http://climate.dot.gov/documents/workshop1002/workshop.pdf
The Potential Impacts of Climate Change on Transportation	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies, Cost Assessment
	Participants:	FHWA
	Location:	NA
	Description:	This project provided an overview of methods available for conducting impacts analyses, including scenario planning, and also discussed adaptation strategy at the federal, state, and local level. This project also investigated costs of specific adaptation measures, and represents one of the more specific sources of quantified information on adaptation costs.
	Project URL:	Workshop report available at http://climate.dot.gov/documents/workshop1002/workshop.pdf
Amtrak Northeast Corridor Electrical Systems Upgrade	Project Type:	Adaptation Strategies
	Participants:	Amtrak
	Location:	Between New Brunswick and Trenton, NJ
	Description:	This project will upgrade a section of Amtrak's overhead electrical wire, which tends to sag and tighten in variable temperatures. Intermediate support structures for overhead wires will be installed to shorten the spans between supporting poles. Funding for the project was awarded by the U.S. Department of Transportation to support higher operating speeds and improve service.
	Project URL:	http://www.amtrak.com/ccurl/903/689/ATK-11-069%20AmtrakAwarded.pdf
Adaptation Activities at the Piscataqua Regional Estuary	Project Type:	Adaptation Strategies
	Participants:	PREP, Maine DOT, NHDOT
	Location:	ME, NH
	Description:	Piscataqua Regional Estuary Partnership (PREP) is conducting outreach on new Maine and New

Activity	Overview	
Partnership		Hampshire culvert and bridge design standards that allows passage of aquatic organisms and stream connectivity, as well as sufficient capacity to prevent catastrophic failures during floods. PREP used evaluation methods to analyze the roads and culverts affected by changes in rainfall and extreme storm events and prioritize stream crossings for repair or redesign.
	Project URL:	http://www.prep.unh.edu/plan.pdf
Adaptation Activities at the Port Authority of NY/NJ	Project Type:	Adaptation Strategies
	Participants:	PATH
	Location:	NY, NJ
	Description:	PATH raised floodgates at the Hoboken station to account for sea level rise. They sealed any gates that were below the 100-year flood plain.
	Project URL:	http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf
International		
Transport for London: Incorporating Adaptation into Asset Management Systems	Project Type:	Impacts/Vulnerability Assessment, Adaptation Strategies
	Participants:	Transport for London
	Location:	London, UK
	Description:	Transport for London (TfL) assessed the climate change risks to their assets and services and incorporated key findings into the agency's risk and asset management systems to adapt primarily to heat and flooding. For example, TfL improved ventilation in the deep tunnels of the London Underground; made structural adjustments to trains and buses to cool the transport vehicles; and mapped areas in the London Underground that are vulnerable to flooding and put in place physical barriers. TfL is also incorporating adaptation measures into the design of new major rail projects.
	Project URL:	http://archive.defra.gov.uk/environment/climate/documents/adapt-reports/06road-rail/transport-london.pdf ; http://www.fta.dot.gov/documents/TfLwebinar15-12-11.pdf ; http://www.sd-research.org.uk/wp-content/uploads/cc_adaptation.pdf ; Case study available at: http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf
Adaptation Activities at	Project Type:	Adaptation Strategies

Activity	Overview
Tokyo Metro	Participants: Tokyo Metro
	Location: Tokyo, Japan
	Description: The city's underground tunnels have triple pumps to increase redundancy to flooding impacts. Additionally, metro ventilation shafts are closed when a heavy rain warning is issued.
	Project URL: http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf
Adaptation Activities in Turkey	Project Type: Adaptation Strategies
	Participants: Various international donors
	Location: Istanbul, Turkey
	Description: A new commuter rail link is built to withstand the 1-in-10,000 year storm with three feet of sea level rise.
	Project URL: http://www.fta.dot.gov/documents/FTA_0001 - Flooded Bus Barns and Buckled Rails.pdf