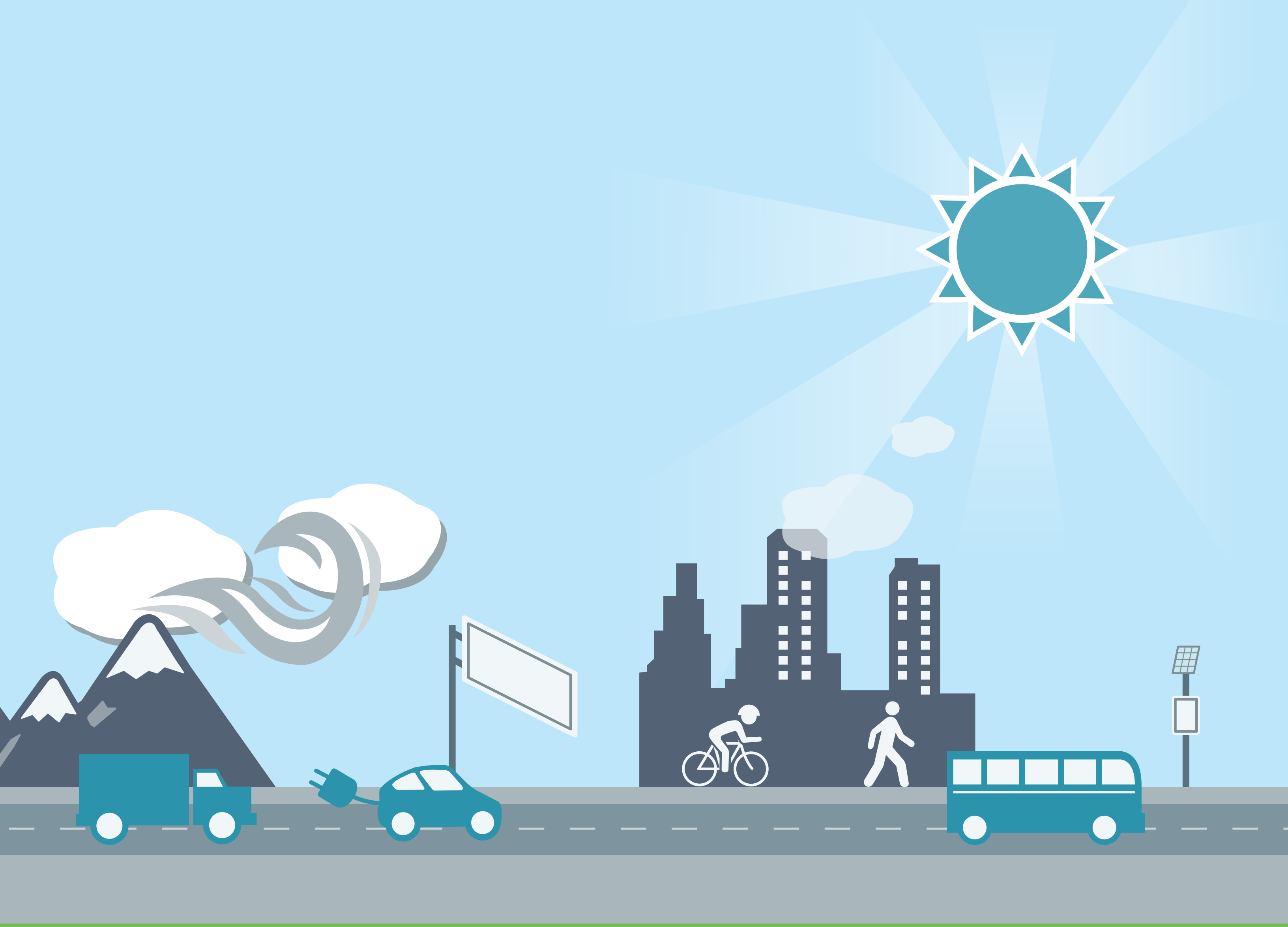
CLIMATE CHANGE ADAPTATION GUIDE

FOR TRANSPORTATION SYSTEMS MANAGEMENT, OPERATIONS, AND MAINTENANCE



U.S. Department of Transportation
Federal Highway Administration

Quality Assurance Statement

Notice

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U.S. Department
of Transportation
**Federal Highway
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1200 New Jersey Ave., SE
Washington, D.C. 20590

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Dear Colleague:

The increased frequency and severity of disasters continue to tax the personnel, resources and capabilities of State and local departments of transportation. Whether it's Transportation Systems Management and Operations (TSMO), maintenance, emergency managers, infrastructure or planning offices – all must respond and adapt to what has become the new reality – one that incorporates the impacts of climate change into the decision making process.

Though transportation agencies have made significant advances in mainstreaming TSMO and maintenance into their core business processes in the past decade, climate change poses a risk to continuing TSMO and maintenance improvements and threatens to erode the public trust in a safe, reliable infrastructure. This is captured in the Federal Highway Administration (FHWA) Order issued in December 2014, in compliance with 2013 Executive Order 13653, *Preparing the United States for the Impacts of Climate Change.*

The challenge in developing this primer, *Climate Change Adaptation Guide*, reflects the challenge inherent in understanding climate change and its impacts on transportation as we know it, i.e., finding ways to help very different and diverse sets of stakeholders understand the benefits of reaching across institutional divides in order to work together to achieve common objectives.

The audience for the primer includes TSMO and maintenance program managers, emergency managers, planners and supervisors involved in all operational aspects that are likely to be affected by climate change. The content features the following:

- Context and Rationale for Adapting to Climate Change,
- What's Already Being Done,
- Steps to Adapt TSMO and Maintenance Programs to Climate Change, and
- How to Get Started.

We look forward to receiving your feedback, reactions, and experiences in implementing these concepts. Please direct any comments, questions, and suggestions to Laurel Radow at Laurel.Radow@dot.gov or Paul Pisano at Paul.Pisano@dot.gov.

Sincerely yours,

Jeffrey A. Lindley
Associate Administrator for Operations
Federal Highway Administration

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Ms. Laurel Radow, Mr. Paul Pisano, and Mr. Robert Hyman, Federal Highway Administration

16. Abstract

This guide provides information and resources to help transportation management, operations, and maintenance staff incorporate climate change into their planning and ongoing activities. It is intended for practitioners involved in the day-to-day management, operations, and maintenance of surface transportation systems at State and local agencies. The guide assists State departments of transportation (DOTs) and other transportation agencies in understanding the risks that climate change poses and actions that can help reduce those risks. Incorporating climate change considerations into how agencies plan and execute their transportation system management and operations (TSMO) and maintenance programs helps the agency become more resilient to unanticipated shocks to the system. Adjustments to TSMO and maintenance programs—ranging from minor to major changes—can help to minimize the current and future risks to effective TSMO and maintenance.

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List of Abbreviations

AADT	average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ADOT&PF	Alaska Department of Transportation & Public Facilities
CAMPO	Capital Area Metropolitan Planning Organization
CMF	capability maturity framework
DOT	department of transportation
ETO	emergency transportation operations
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
LOS	level of service
MDOT	Michigan Department of Transportation
MDSHA	Maryland State Highway Administration
MnDOT	Minnesota Department of Transportation
MPO	metropolitan planning organization
MTC	Metropolitan Transportation Commission
NCHRP	National Cooperative Highway Research Program
RWIS	Road Weather Information System
SEPTA	Southeastern Pennsylvania Transportation Authority
TOC	traffic operations center
TRANSCOM	Transportation Operations Coordinating Committee
TSMO	transportation systems management and operations
USGS	United States Geological Survey
WSDOT	Washington State Department of Transportation

I. Introduction to this Guide

Ensuring safety, reliability, and mobility guides the functioning of department of transportation (DOT) transportation systems management and operations (TSMO) and maintenance programs around the country. With the infrastructure mostly built out, and in many cases reaching the end of its lifespan, the emphasis on TSMO and maintenance has continued to grow at both State and local levels.

Transportation agencies have made significant advances in mainstreaming TSMO and maintenance into their core business processes over the last decade. Investments in technology and systems for traffic monitoring and management, traffic incident management, and to provide traveler information have supported the capability of agencies to monitor, respond to, and communicate conditions to travelers. Similar improvements in maintenance management have occurred with use of material management systems, improved maintenance and construction strategies, and more robust asset management techniques.

Climate change poses a risk to continuing improvements in this area and threatens to erode the public trust in a safe, reliable infrastructure.[1] DOTs are already observing and responding to the impacts of climate change. Infrequent but extreme weather events (e.g., floods, hurricanes, Southern snowfalls) are becoming more frequent, and long-term climatological trends are slowly but inexorably changing how transportation systems will need to be planned, designed, operated, and maintained.[2]

Transportation Systems Management and Operations (TMSO), Maintenance, and Climate Change

State department of transportation (DOT) TSMO and Maintenance Programs are vulnerable to climate change. Climate change increases uncertainty around planning for extreme weather events, since the past is no longer a reliable predictor of the future. Climate changes could result in:

- Loss of roadway capacity.
- Loss of alternative routes.
- Loss of situational awareness (due to power/communications outages).
- Inability to evacuate.
- Loss of service life (due to faster deterioration).
- Increased safety risk.
- Loss of economic productivity.
- Reduced mobility.

1 M. D. Meyer, E. Rowan, C. Snow, and A. Choate, *"Impacts of Extreme Weather on Transportation: National Symposium Summary,"* American Association of State Highway and Transportation Officials (AASHTO), June 29, 2013. Available at http://climatechange.transportation.org/pdf/2013_symposium/AASHTO_EWESymposium_2013.pdf.

2 M. Meyer et al., NCHRP Report 750: *Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System,* Washington, DC: Transportation Research Board of the National Academies, 2014. Available at: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_750v2.pdf.

Climate change risks are as yet not well-understood by TSMO and maintenance groups. Most of the discussion around climate risks has been at a long-term planning level or from an infrastructure design standpoint. Consequently, adapting to climate change is still new to the operating divisions within the DOT. Many agencies are, nevertheless, finding that the approaches and practices that made them successful operators and maintainers of facilities are not adequate—or at least need to be revisited—with this change in climate. More frequent events, unusual phenomenon, and changes in long-standing patterns combined with steadily increasing funding and workforce pressures put agencies at a crucial juncture on how to plan for effective operations and maintenance.

Incorporating climate change considerations into how agencies plan and execute their TSMO and maintenance programs helps the agency become more resilient to unanticipated shocks to the system. Adjustments to TSMO and maintenance programs—ranging from minor to major changes—can help to minimize current and future risks to effective maintenance and operations.

This guide provides information and resources to help DOT TSMO and maintenance staff incorporate climate change into their planning and ongoing activities. It will assist State DOTs and other transportation agencies to understand the risks that climate change poses and actions that can help reduce those risks. Although there is continually new information emerging about anticipated risks and strategies to address them, there is sufficient information to begin a more concerted effort to evaluate programs and begin to make or plan to make adjustments today.

Figure 1. Illustration. Frequent Questions from Transportation Systems Management and Operations (TSMO) and Maintenance Program Managers.

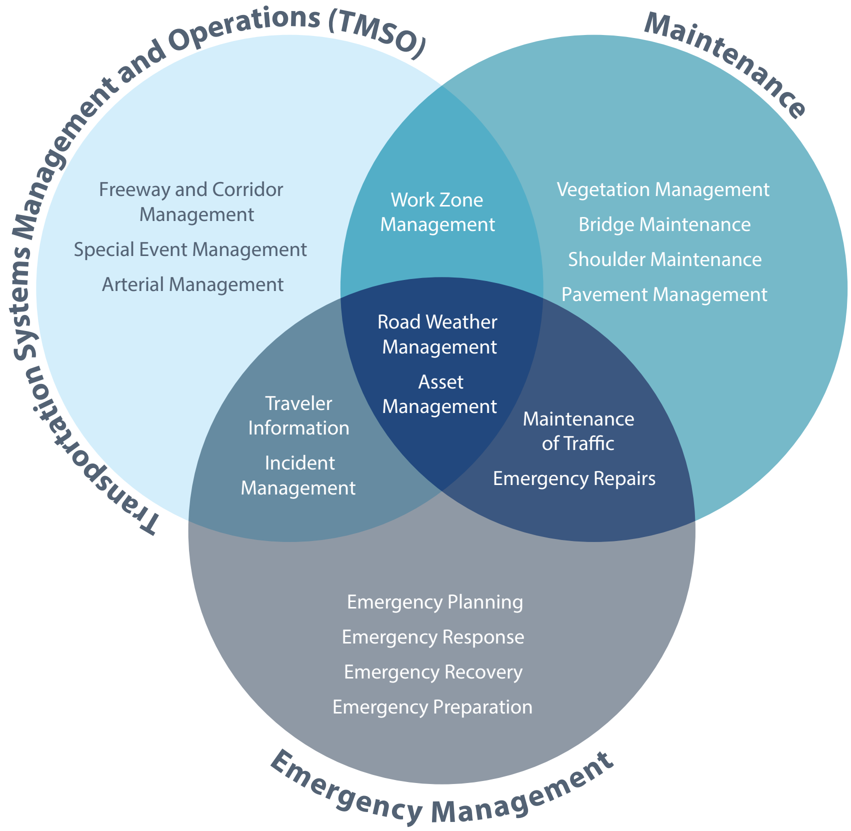

Figure 2. Graph. Overlapping Responsibilities of Different Transportation Agency Offices.

A. Who Should Use this Guide?

This guide is meant for practitioners involved in the day-to-day management, operation, and maintenance of surface transportation systems at State and local agencies. Climate change will affect different offices and their varying responsibilities in different ways. As shown in Figure 2, some responsibilities among this staff are also overlapping and will require coordination. For example, DOT emergency management staff and TSMO staff need to coordinate during an emergency to provide accurate and up-to-date traveler information. In some DOTs, staff may serve both a TSMO and maintenance function. All staff might have a role in major emergencies. In a majority of functional areas, TSMO and maintenance depends on the collaboration between multiple agencies.

Unless otherwise specified, the content in the guide is applicable to all:

- State and local DOT TSMO and maintenance managers.
- State and local DOT planning staff.
- Metropolitan planning organization (MPO) staff.
- State and local DOT emergency management staff.

B. How Will this Guide Help Agencies Adapt?

The guide provides the rationale and specific guidance for integrating the capability for climate change adaptation and extreme weather response into TSMO and maintenance programs. It also articulates why doing so will lead to greater sustainability.

In laying out both the need for integration of adaptation into decision making and approaches to do so, this guide also takes a first step toward beginning to establish a consistency of language and practice that will facilitate much-needed collaboration and coordinated action across operating groups within and outside the agency.

The guide provides resources to help agencies:

- Self-evaluate where practices need to be altered to enhance resiliency to climate change.
- Identify what changes need to be made.
- Assess the benefits and co-benefits of making those changes.
- Map out the changes in capabilities that need to be taken to implement them.

C. What this Guide Does Not Cover

The guide is a first effort to provide guidance on how to adapt TSMO and maintenance programs to climate change. This is a quickly evolving field as evidenced by the rapidly emerging research by top-level national and international agencies (e.g., United Nations, National Academies). There are still many knowledge gaps in terms of adapting practices, including risk management and probabilistic decision making. This document reflects what is known today, but does not answer all the questions that practitioners are certain to raise.

The guide also does not provide guidance on related topics that are better described in other documents (e.g., how to respond during extreme or adverse weather). As mentioned above, this guide is focused on helping agencies do the "up-front" work to prepare for addressing climate change and extreme weather events.

D. How to Use this Guide

The guide provides context, an overview of steps, and specific resources to help DOTs get started to adapt TSMO, maintenance and emergency management programs to climate change. Users may come to the guide with varying levels of familiarity with the content and issues presented herein. It is, thus, designed so that the Table of Contents can be used to jump to any section in the guide where users find content relevant to their specific needs. Of particular note:

- Section IV describes the general planning components needed to adapt a TSMO and maintenance program for climate change.
- Blue text boxes throughout the guide (titled **"Getting Started"**) contain specific resources to help agencies get started with adaptation, such as checklists and other resources.
- Green text boxes throughout the guide (titled "**Examples from the Field"**) provide lessons learned and best practices from around the country. These examples help to illustrate the more general guidance provided and highlight the diversity of issues and approaches to addressing them.

Getting Started

Examples from the Field

II. Context and Rationale for Adapting to Climate Change

A. Federal Highway Administration Action on Climate Change

Federal Highway Administration (FHWA) recognizes that climate change and extreme weather events pose a significant challenge to the safety, reliability, effectiveness, and sustainability of the national transportation system. In 2014, FHWA issued a directive that establishes FHWA policy on preparedness and resilience to climate change and extreme weather events, in compliance with Executive Order 13653, *Preparing the United States for the Impacts of Climate Change*, issued in 2013. The FHWA directive provides several ways in which "FHWA will integrate consideration of the risks of climate change and extreme weather event impacts and adaptation responses, into the delivery and stewardship of the Federal-aid and Federal Lands Highway programs," including encouraging State departments of transportation (DOTs), metropolitan planning organizations (MPOs) tribal governments, and others to develop cost-effective strategies to minimize climate and extreme weather risks.[3]

FHWA began activities to address climate change in the early 2000s with several white papers followed by in-depth studies on the impacts of both climate variability and climate change in the Gulf Coast as well as sea level rise on the Atlantic Coast. FHWA's next steps to address climate change were to develop tools and information that could be used by State DOTs and MPOs to assess their vulnerabilities to climate change. FHWA also continues to analyze strategies that can help improve resiliency. For additional information on FHWA's climate change efforts, see the FHWA web page, "Summary of FHWA Climate Adaptation Initiatives." [4]

The FHWA Order and ongoing research activities are intended to promote transportation system resiliency, defined as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. Much of the work to date has been focused on assessing vulnerabilities and considering transportation infrastructure and design adaptation. This guide specifically focuses on how agencies can reframe TSMO and maintenance programs to increase resilience to the uncertainty and variability associated with climate change.

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3 FHWA, Order 5520, Subject: Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events, December 15, 2014. Available at: *http://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm*.

4 FHWA, "Summary of FHWA Climate Adaptation Initiatives" Web page. Available at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/summary/index.cfm*.

B. What is Transportation Systems Management and Operations and Maintenance?

This guide focuses on two primary transportation functions: 1) transportation systems management and operations (TSMO) and 2) maintenance. These functions both involve the day-to-day activities that maximize the use of transportation infrastructure. TSMO refers to an integrated approach of programs, projects, or services designed to get the safest and most efficient use out of existing and planned infrastructure. TSMO functions include traffic management, traffic incident management, traveler information services, traffic signal coordination, transit priority/integration, freight management, work zone management, planned special event management, road weather management, and active transportation and demand management.

Maintenance activities help to preserve and extend the use of transportation infrastructure and aim at carrying out day-to-day protective and repair measures to limit degradation due to natural processes (e.g., weather) or imposed processes (e.g., traffic). Maintenance functions include pavement management, shoulder maintenance, bridge inspection, vegetation management, road weather management, work zone management, and asset management.

C. How are Extreme Weather Events and Climate Change Related?

It is important to understand how extreme weather events and climate change are related and how they differ.[5] Changes in climate and weather are linked over the long term, but no single weather event can specifically be attributed to a changing climate.

- Weather events are defined as the state of the atmosphere in a particular location at a particular time. For example, rain, temperature, and wind are all aspects of local weather. "Extreme weather events can include significant anomalies in temperature, precipitation and winds, and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires and windstorms (including tornadoes and tropical storms)." [6]
- Climate change refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events now and in the future.[7]

Long-term trends in climate are not dependent on any single extreme event. A single large rain event or even a single wet year may just be a normal fluctuation in weather patterns but changes that are noted year after year, such as a run of wet years, can be attributed to a larger change in the climate.

Climate change could mean that what was historically a rare weather event becomes increasingly frequent (possibly shifting from rare to occasional or regular). Consideration of how we respond effectively or not to the rare extreme events occurring today can provide useful information about how we can and should respond to increasing future risk. Optimizing for today's extreme weather events makes our systems more prepared for the increased frequency of some events that is anticipated under a changing climate. Figure 3 demonstrates the shift in temperatures towards more hot weather and a slight decrease in cold weather.

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5 A good discussion of the linkage between extreme weather events and climate change can be found in: D. Huber and J. Gulledge, "Extreme Weather and Climate Change: Understanding the Link and Managing the Risk," Science and Impacts Program (Arlington, VA: Center for Climate and Energy Solutions, 2011). Available at: http://www.c2es.org/publications/extreme-weather-and-climate-change.

6 FHWA Order 5520, December 15, 2014. "Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events." Available at: http://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm.

7 Ibid.

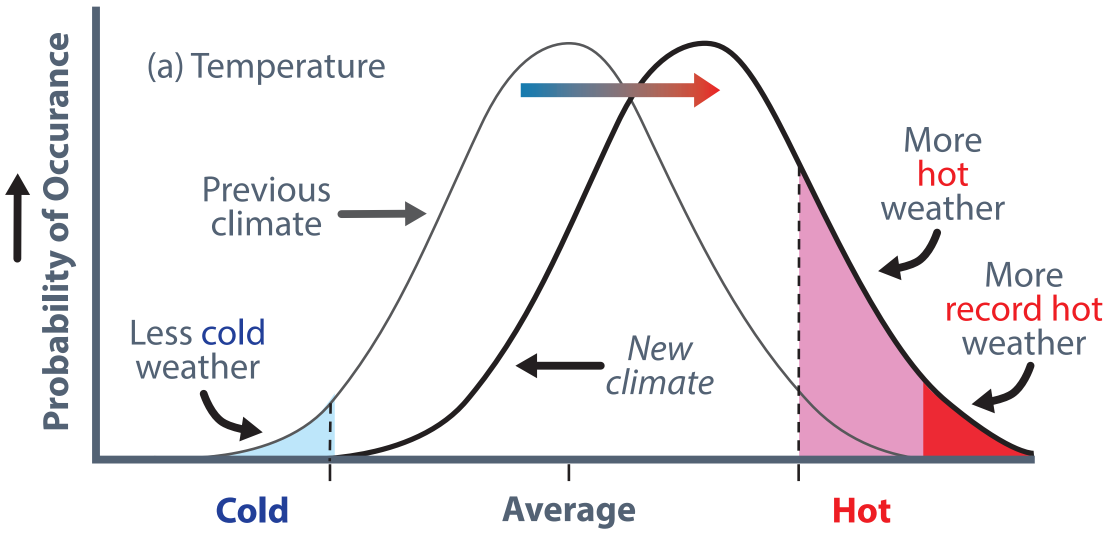

Figure 3. Graph. Weather Probability Distribution Showing an Increase in Mean Temperature.[8]

D. How Will Climate Change Affect Transportation Systems Management and Operations and Maintenance?

As climate changes, agencies may have to deal with new weather stressors that require different planning approaches or responses (e.g., loss of permafrost in Alaska, snow and ice control in Southern states). The 2011 report, *Adapting Transportation to the Impacts of Climate Change State of the Practice* provided an overview of the operational impacts associated with climate change.[9] These operational impacts include:

- Increase in traffic incident management activities.
- Road and lane closures.
- Reduced (and variable) speed limit.
- Disruption of transit service.
- Road and transit diversions.
- Truck restrictions.
- Work zone management (to accommodate additional lane closures).

The 2013 report, *Planning for Systems Management & Operations as part of Climate Change Adaptation*, provides a summary of the anticipated changes to system maintenance (e.g., inspection, frequency of repairs, need for "quick maintenance" patrols); system operations practices and strategies (e.g., more frequent diversion to more robust alternate routes); travel behavior (e.g., motivation to use alternate modes of transport such as transit, biking, or walking); and freight transportation (dynamic or seasonal restrictions for trucks or rail during times of high heat) needed or likely to occur as a result of anticipated impacts of climate change.[10]

8 Peterson, T.C., D.M. Anderson, S.J. Cohen, M. Cortez-Vázquez, R.J. Murnane, C. Parmesan, D. Phillips, R.S. Pulwarty, J.M.R. Stone, 2008: Why Weather and Climate Extremes Matter in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands.* T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC. Available at: *https://downloads.globalchange.gov/sap/sap3-3/sap3-3-final-all.pdf.*

9 Transportation Research Board Special Task Force on Climate Change and Energy, Transportation Research Circular E-C152: Adapting Transportation to the Impacts of Climate Change State of the Practice 2011, June 2011. Available at: *http://onlinepubs.trb.org/onlinepubs/circulars/ec152.pdf.*

10 FHWA, Planning for Systems Management & Operations as Part of Climate Change Adaptation, FHWA-HOP-13-030 (Washington, DC, 2013). Available at: *http://ops.fhwa.dot.gov/publications/fhwahop13030/index.htm.*

While TSMO and maintenance programs are often reactive by nature, the accelerating pace and increasingly unpredictable nature of extreme weather events could place increasing strain on an already stressed system. Further, agencies may not be optimized for the present; some practices need to be improved now.

TSMO and maintenance programs will need to take a proactive approach to regularly reevaluate existing programs and practices in light of new information and criteria (e.g., if preparing for new demands, they may need to adjust budgets) to ensure they are climate resilient. Opposition to making changes in operations may exist due to the risk-averse environments under which many State DOTs operate. Traditionally, this risk aversion has resulted in slow changes in practices and protocols in order to avoid changing what works. Transportation agencies could be at greater risk, however, if they do not change their practices rather than if they do. The environment in which they work is changing due to climate change; risk-averse decision makers should seek to avoid risks by considering climate change in their systems management and maintenance rather than ignoring it.

E. Why Do Transportation Systems Management and Operations and Maintenance Programs Need to Adapt to Climate Change?

TSMO and maintenance programs have vital roles to play in adapting to climate change. For many of the already observed and anticipated weather events related to climate change, TSMO and maintenance workers as well as the DOT emergency responders with whom they coordinate—who are, in some instances, DOT maintenance staff—are and will be the public face and the front-line of the response. Climate change presents a business risk for transportation agencies. Without proactive steps to anticipate potential changes and respond to them, the ability of agencies to support their core mission could be compromised.

With climate change comes uncertainty, be it in a greater variability of expected events or unexpected extreme weather. By not understanding the risk or not assessing the vulnerability of their operations, agencies can be caught off-guard by an unexpected event leading to significantly degraded capabilities when they are most needed.

Changes in relatively short duration extreme events often result in the most significant consequences, and while DOTs may be prepared to respond to these events on an individual basis, the cumulative impact of more severe and more frequent events may warrant a change in business practices. Longer term changes to annual or seasonal averages, which are often cited in broad-scale summaries of projected climate change, cause less immediate impacts but over time can affect practices and costs.

Not all the necessary adjustments to business practices are radical; there are many ways—big and small—to account for climate change and reduce this business risk. In fact, many TSMO and maintenance adaptations will be the "low-hanging fruit" to prepare DOTs for climate change, in contrast to changes to infrastructure design.

Incremental steps toward a more comprehensive program that fully considers how to incorporate potential climate change impacts will be easier for most agencies to manage than an immediate, full-fledged, comprehensive overhaul of their existing programs. A phased implementation approach will enable agencies to adapt their TSMO and maintenance programs to climate change in a planned and systematic manner. For this to occur, it is necessary to incorporate the needs of climate change and extreme weather events into the routine policy and practice of TSMO and maintenance at transportation agencies.

Adapting TSMO and maintenance programs is largely about improving capability rather than a major technology development and deployment initiative. Many of the technology elements used to support safety, congestion mitigation, and traveler information objectives are already in place and there is more on the way. For example, today Road Weather Information Systems (RWIS), cameras, and other roadside infrastructure are used extensively by agencies around the country. In the near future, connected vehicle technologies promise to overcome the barriers of fixed infrastructure and data availability. To adapt to climate change then, agencies need to consider how these existing capabilities need to evolve to meet the new and emerging requirements of a changing climate. These may take the form of hardening the communication links or rethinking the siting of these detection systems. Similarly, other existing processes for supporting safety and reliability need to be reviewed and supplemented to account for climate change.

F. Capability Maturity Framework

The American Association of State Highway and Transportation Officials (AASHTO) and FHWA have developed a capability maturity framework (CMF) to help DOTs adapt their TSMO programs.[11] The CMF defines six areas of capability that form the supportive foundation for the implementation of TSMO strategies. As agency capabilities increase from ad-hoc implementation and planning to optimized practices, agencies will be able to have repeatable processes that are scalable, sustainable, and mainstreamed.

This guide aligns those actions needed to adapt TSMO and maintenance programs to climate change with the six areas of the CMF:

- **Business processes** – including financial (e.g., budgeting) as well as conducting risk analyses and dealing with uncertainty, planning, programming, and standard operating/implementation procedures.
- **Systems and technology** – transportation agencies have invested in a wide suite of technology and management systems to enable them to more efficiently manage weather events within their jurisdiction.
- **Performance measurement** – including measures definition, data acquisition, analysis, and utilization.
- **Culture** – including technical understanding, leadership commitment, policy, outreach, and program authority.
- **Organization and workforce** – including organizational structure, staff capacity, development, and retention.
- **Collaboration** – including internal collaboration and relationships with other public agencies and the private sector.

G. What's Already Being Done?

The growing awareness that climate change can affect transportation has not yet resulted in widespread actions to identify and implement strategies to address climate change. Some transportation agencies have begun to assess vulnerability. Fewer have moved beyond vulnerability assessments and into adaptation planning. Even fewer have implemented adaptation strategies and begun to evaluate their effectiveness. Further, more emphasis to date has been on the implications of climate change for infrastructure planning, design, and engineering with less focus on system management, operations, and maintenance.

The transportation sector is not ahead or behind other sectors in this regard. Changes in climate are often discussed on a global or regional scale and presented with wide ranges of uncertainty and timescales. It is challenging to understand what climate change will mean on a local scale and for the timeframe most relevant to specific decision making processes of interest.

11 See the AASHTO "Transportation Systems Management and Operations" web page for more information: http://www.aashtotsmoguidance.org/.

III. Steps to Adapt Transportation Systems Management and Operations and Maintenance Programs to Climate Change

A. How Transportation Systems Management and Operations and Maintenance Work Together on Climate Change

Over the past 10 years, State and local agencies have implemented various transportation systems management and operations (TSMO) and maintenance strategies to mitigate the impacts of adverse weather on the transportation system. The strategies run the gamut from plowing and sanding to coordinated traffic control strategies and regional traveler information. Agencies respond to weather events through a multi-pronged approach that involves a combination of operational, maintenance, and, at times, emergency management strategies. Typical strategies used today include motorist alerts, advisories, warnings (which include roadside active warning systems and pre-trip traveler information systems), speed restrictions (variable speed limits, for example), vehicle restrictions (truck restrictions during high winds), route restrictions (road closures), anti-icing/deicing road surface treatments, plowing, and traffic signal management (weather responsive traffic management). In addition, traffic incident and emergency management practices provide agencies with the ability to marshal resources effectively to address adverse weather. Most of these approaches require multi-agency and multi-disciplinary capabilities to be brought together efficiently before, during, and after the extreme weather event. Traffic incident and emergency management collectively fall under the area of emergency transportation operations (ETO), which involves collaboration and coordination between transportation, public safety (fire, rescue, emergency medical service [EMS]), law enforcement) and emergency management communities.

The roles and responsibilities of TSMO, maintenance, and emergency response managers and staff are connected and often interdependent in addressing the impacts of extreme weather and climate change on the transportation system. Each functional group has a unique set of decisions falling across the six areas of the capability maturity framework (CMF) (described in Section II) that may need to be examined in adapting to climate change.

For example, the managers of maintenance programs will be concerned with decisions involving pavement rehabilitation needs and methods, bridge maintenance needs and methods, construction and maintenance work timelines and timeframes, and vegetation control. TSMO program managers will need to revisit other decisions such as the types of monitoring equipment and sources, communication needs, and siting criteria necessary to obtain real-time operational information on the transportation system and push information out to travelers. Emergency management leaders, in coordination with operations divisions, will look at adapting operating procedures and resource levels to prepare for hurricane evacuations or other weather-related emergencies. As is evident, TSMO functions rely on well-maintained infrastructure, and successful emergency management depends on reliable and strategically deployed TSMO infrastructure (e.g., traffic signals, contra-flow lanes, variable message sign (VMS), cameras, road weather information stations), TSMO staff, and fine-tuned operating procedures that can be leveraged during emergencies. The same holds true for maintenance, its infrastructure, and the linkage between maintenance and emergency management.

The link between transportation operations and emergency management varies depending on the scale of the event. During major, catastrophic events emergency management agencies have control of the response and transportation operations. During less extreme events, the departments of transportation (DOTs) maintain control over the highways and major arterials. This difference will be important to consider when DOTs plan actions to address climate change risks in the short and long term. Figure 4 illustrates that as the level of severity of the incident increases, the number of agencies involved grows beyond the DOT to include public safety and emergency management agencies. The increase in severity also indicates that a greater level of collaboration and communication between agencies and functions is required.

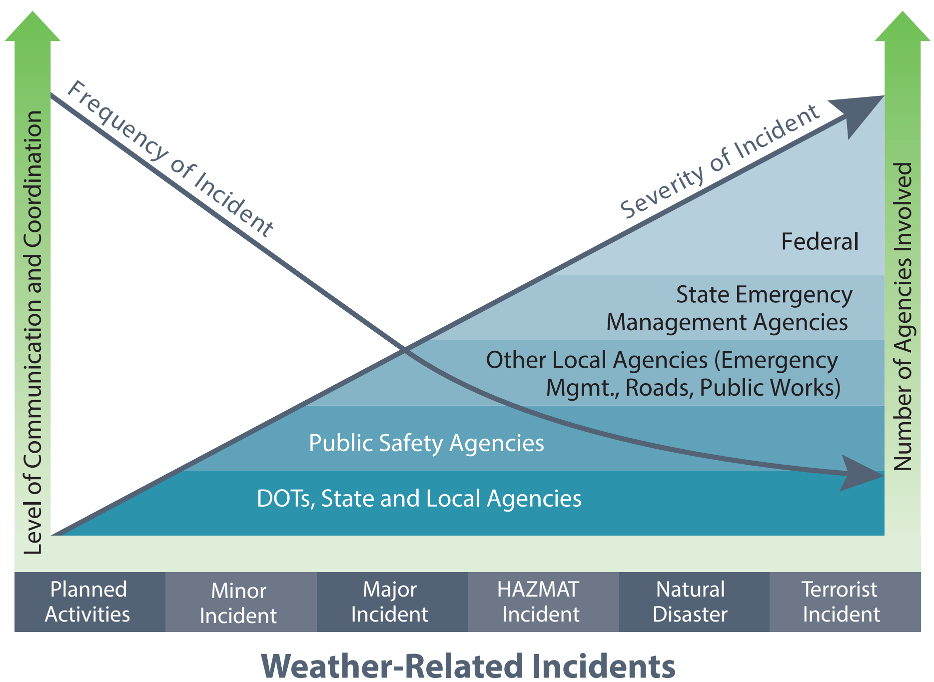

Figure 4. Graph. Involvement of Agencies in Incident Response.[12]

12 S. Lockwood, J. O'Laughlin, D. Keever, and K. Weiss, NCHRP Report 525: Surface Transportation Security Volume 6 – Guide for Emergency Transportation Operations, Washington, DC: Transportation Research Board of the National Academies, 2005. Available online at: *http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_525v6.pdf*.

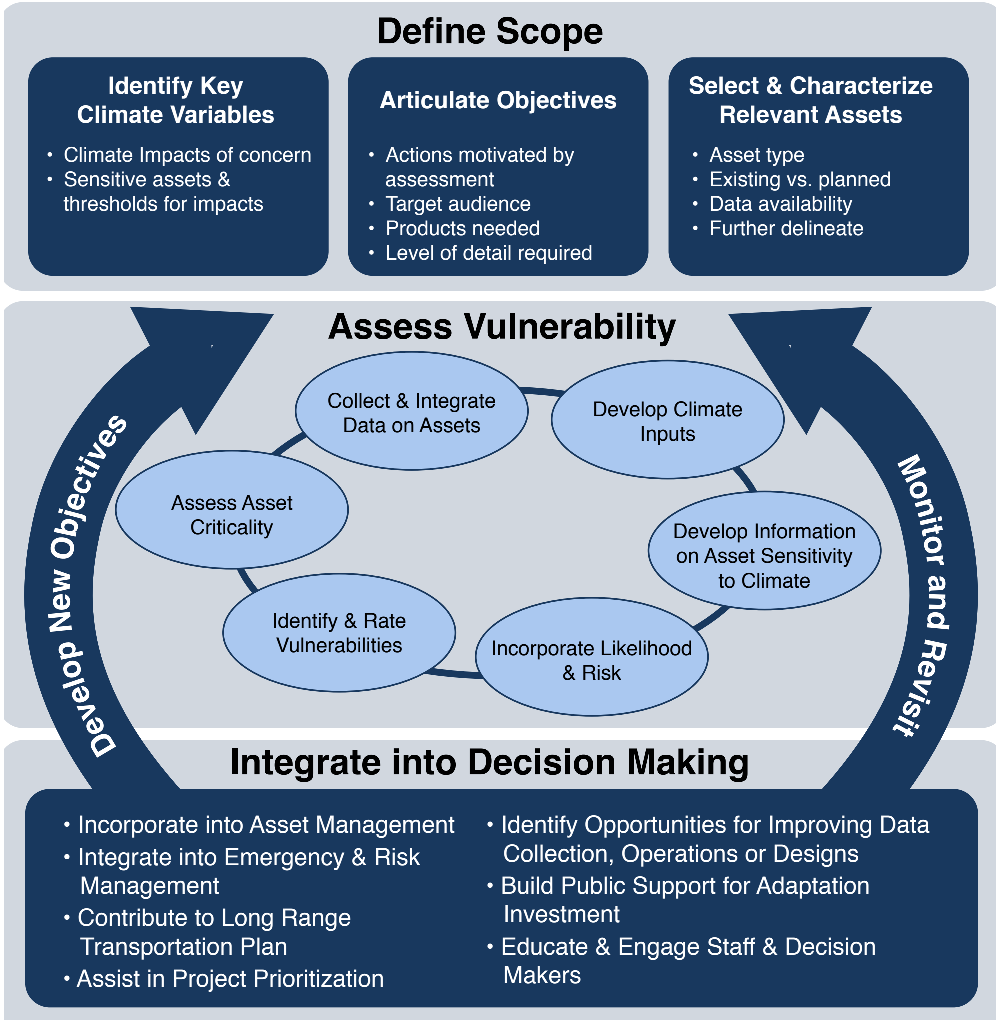

Figure 5. Diagram. Federal Highway Adminstration (FHWA) Climate Change and Extreme Weather Vulnerability Assessment Framework.

B. Overview of an Operations Adaptation Framework

The Federal Highway Administration (FHWA) has developed and tested a Climate Change and Extreme Weather Vulnerability Assessment Framework ("the Framework") (see Figure 5) which consists of a report[13] and an online virtual framework (see Figure 6),[14] which serve both as a guide and a collection of resources for use by transportation professionals when analyzing the impacts of climate change and extreme weather on transportation infrastructure. Its purpose is to identify key considerations, questions, and resources that can be used to design and implement a climate change vulnerability assessment. To date, the Framework has been tested by 24 pilot sites and has undergone a series of refinements as a result of the real-world findings. The pilots have also contributed to the plentiful body of lessons learned and example resources that are linked to the virtual version of the Framework.

13 FHWA, Climate Change and Extreme Weather Vulnerability Assessment Framework, FHWA-HEP-13-005 (Washington, DC, 2012). Available at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/vulnerability_assessment_framework/page01.cfm*.

14 FHWA, Virtual Framework for Vulnerability Assessment. Available online at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/*. Last accessed June 28, 2015.

The Federal Highway Administration (FHWA) Virtual Framework

FHWA has developed a broad set of resources to help transportation agencies prepare for climate change. The "Virtual Framework for Vulnerability Assessment" website houses resources for State and local transportation agencies (see Figure 6). The Virtual Framework breaks the vulnerability assessment process into six modules. Each module contains step-by-step guidance, video testimonials from professionals sharing lessons on their experience, case studies related to the framework step, links to resources related to the step, and tools to help a user complete the step.

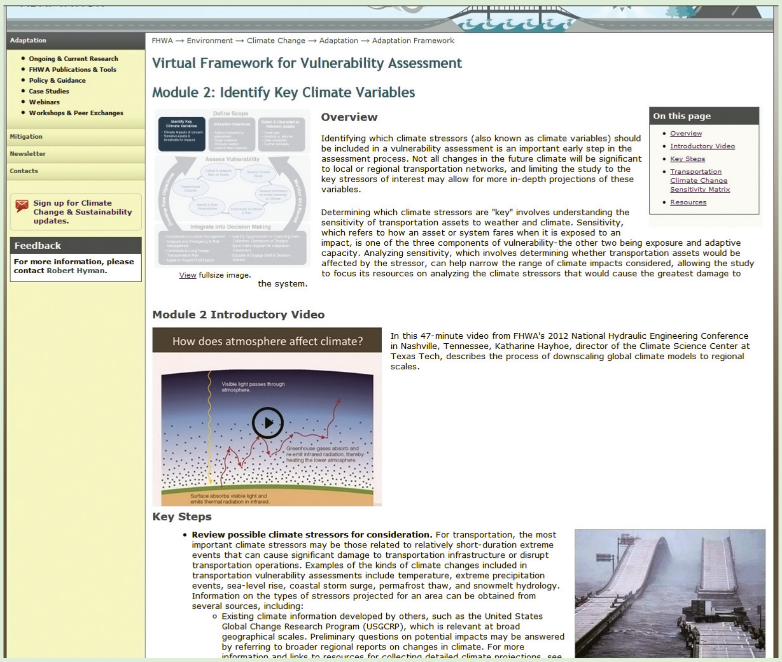

Figure 6. Screenshot. Federal Highway Administration Virtual Framework for Vulnerability Assessment (Module 2 shown).

This guide is intended to complement the resources on the Virtual Framework and provide targeted guidance to staff in the transportation systems management and operations (TSMO) and maintenance domains. Throughout this document, the Virtual Framework is referenced as appropriate, in cases where guidance (e.g., where to find climate data) is not operations-specific.

The Framework, originally developed with an infrastructure planning and design focus, provides the organizing principle for understanding adaptation needs from an operations and maintenance perspective as well.

Consistent with the Framework the primary components of this guide include:

- Define objectives and scope.
- Assess vulnerability.
- Integrate climate change considerations into decision making.
- Monitor, revisit, and develop new objectives.

While the emphasis of this guide is on concrete actions DOTs can take to integrate climate change into decision making, it is critical to also define the scope of adaptation efforts and assess vulnerabilities to inform the development of adaptation strategies. Figure 7 illustrates how TSMO and maintenance groups can use the Framework to identify and implement appropriate strategies for their unique conditions and locations.

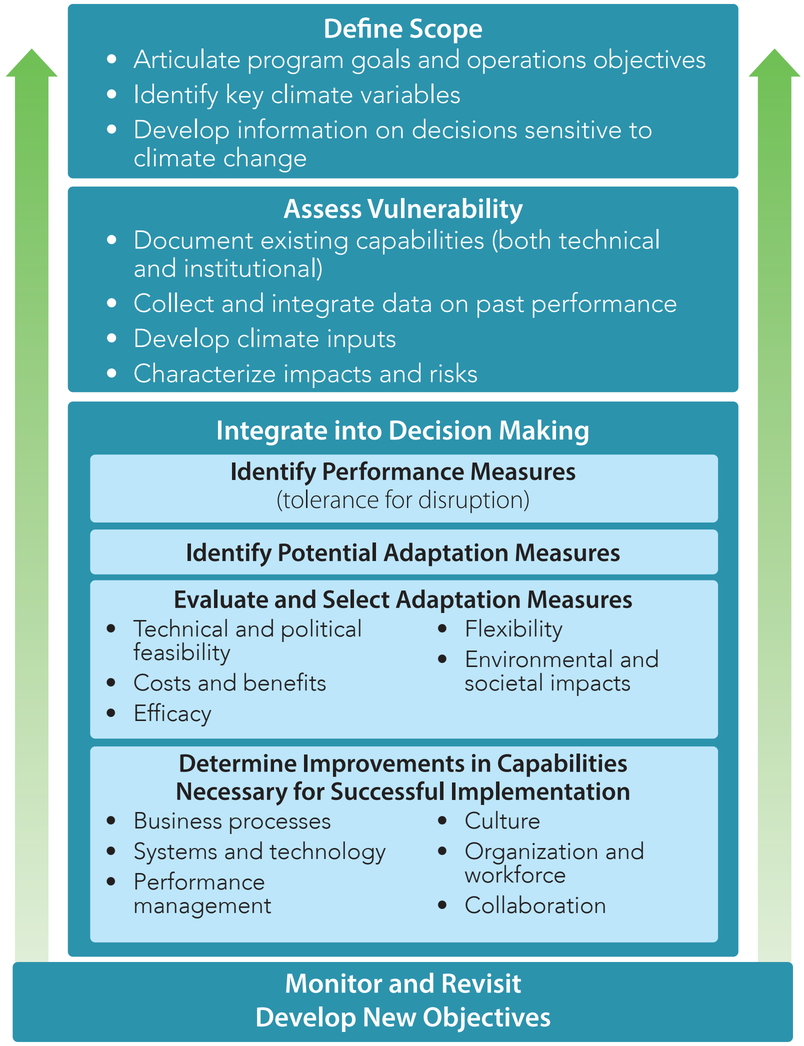

Figure 7. Diagram. Climate Change and Extreme Weather Transportation Systems Management and Operations (TSMO) and Maintenance Adaptation Framework.

C. Define Scope

It is important to articulate the objectives of the adaptation effort up front and identify the anticipated changes in climate that are most relevant to your agency. Together, these steps frame the scope of the planning effort and drive the details required; they help minimize data collection and analysis activities that would ultimately be extraneous to the desired objectives.

1. Articulate Program Goals and Operations Objectives

TSMO and maintenance offices within agencies have long been driven by goals and objectives largely around safety, levels of service, and reliability. DOTs need to adapt to climate change to ensure they can continue to meet program goals.

Program goals and operations objectives may require some updates when anticipated climate changes are taken into account. These updates may be only subtle shifts in agency focus, but should aim to define what must be achieved to ensure resilient operations. Agencies should consider what levels of performance are expected during adverse weather (which may become more frequent or intense under a changing climate) and what levels of disruption are tolerable. Demand-oriented goals and objectives (e.g., the role of the agency. in serving the surge in demand that may be expected) need to be defined as well as the expectations for restoration of services and travel.

Getting Started: Obtaining Buy-In

A critical component to any organizational change is developing support for that change among key decision makers and stakeholders. Adapting a transportation systems management and operations (TSMO) or maintenance program to increase climate change resiliency requires gathering support among program management, agency decision makers, program staff, and others involved in the TSMO or maintenance program activities. The level of buy-in required will depend on the scale of change desired. Below are several recommendations for gathering support for adapting a TSMO or maintenance program to prepare for the current and potential future impacts of climate change:

- Make the business case for resilience.
  - Start by identifying any current issues in operating and maintaining the transportation system as a result of extreme weather events or noticeable changes in climate.
  - Use FHWA documents, such as the *Regional Climate Change Effects: Useful Information for Transportation Agencies*, to gather key reasons to be concerned about climate change and what the projected effects are of climate change locally.[15]
  - Find a model or example to strengthen the case. The Federal Highway Admintration (FHWA) has several case studies available.
- Engage staff and leadership throughout the department of transportation (DOT) early and often, especially in the vulnerability assessment and brainstorming of adaptation strategies.
- Establish clear roles and responsibilities for individuals within the organization and determine systems for accountability.
- Improve integration of TSMO, maintenance, and emergency management into DOT planning for climate change.

Agencies should also develop more specific, outcome-based operations objectives for the program goals. These operations objectives should be refined and tied to specific performance measures when working through Sections III.D. Assess Vulnerability and III.E Integrate into Decision Making (and once the user has a better understanding of realistic expectations that take into account future changes in climate).

2. Identify Key Climate Variables

Changes in climate and extreme weather events will not be uniform throughout the world or even throughout the United States. It is important to identify the climate stressors or extreme weather events (e.g., increase in extreme heat, more frequent heavy precipitation, increased precipitation variability, drought, flooding, sea level rise, higher storm surges, increase in wildfire probability) that: (1) could occur locally; and (2) could affect local TSMO and maintenance programs. Examples of the geographic diversity of climate impacts can be seen in Figure 8. A complete set of resources for identifying local climate changes is available as part of Module 2 of FHWA's Virtual Framework for Vulnerability Assessment.[16] Once the regional climate stressors of concern have been identified, Section III of this document explains how to refine DOTs understanding of the scale and impacts of those climate stressors on TSMO and maintenance.

15 FHWA, Regional Climate Change Effects: Useful Information for Transportation Agencies, May 10, 2010. Available at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/climate_effects/*.

16 Module 2 of the FHWA Virtual Framework is available online at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules/index.cfm?moduleid=2*.

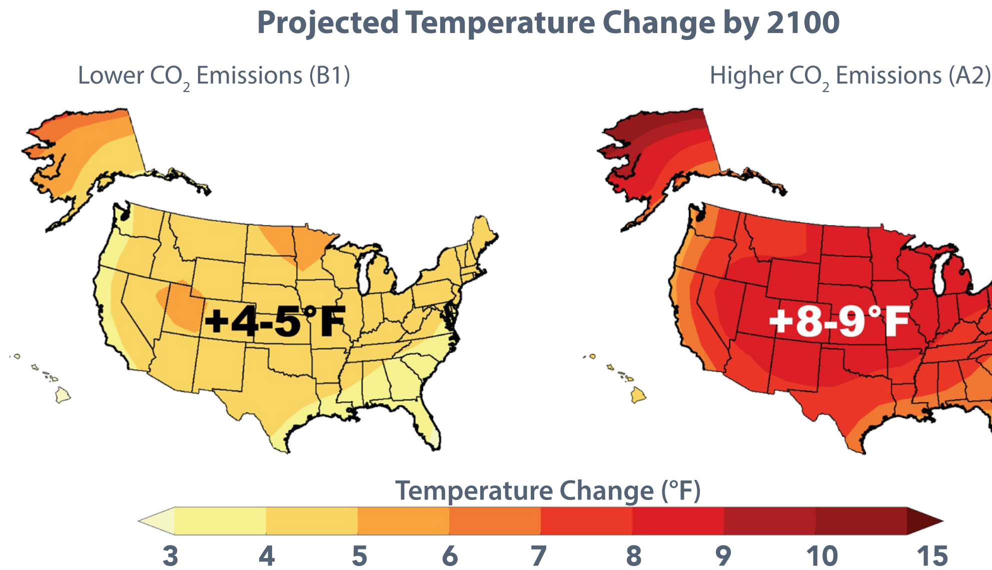

Figure 8. Chart. Projected Temperature Changes under Low and High Emissions Scenarios.[17]

3. Develop Information on Decisions Sensitive to Climate Change

As discussed in Section III.D.2, information on the past climate and the resultant impacts is useful for understanding the kinds of weather and climate effects to which assets and operations are sensitive and can help to identify thresholds beyond which future climate effects may affect those assets.

Sensitivity = how an asset or system fares when it is exposed to an impact.

Source: Federal Highway Administration Virtual Adaptation Framework.

It is also important to look forward and identify decisions that may be climate-sensitive in the future and which decisions (e.g., standard operating practices, budget allocations) may be based on historical climate trends that no longer accurately reflect more recent trends (that have shifted due to climate change).

The following is a proposed definition for climate-sensitive decisions:

Decisions are climate-sensitive if their continued effectiveness could be compromised by projected changes in climatic conditions (e.g., changes in temperature, precipitation, weather patterns, and the frequency and intensity of extreme weather events).

TSMO and maintenance decisions that DOTs make on a daily basis are rarely climate-sensitive, because the implications of those decisions are typically so short-lived that there is not enough time for them to be compromised by the effects of climate change. Transportation agencies make numerous short-term and long-term decisions about their TSMO and maintenance programs, however. Potential changes in extreme weather events or climate variability are relevant to many of these decisions, especially the decisions agencies make infrequently.

17 J. Walsh, D. Wuebbles, et al. Climate Change Impacts in the United States: The Third National Climate Assessment, "Ch. 2: Our Changing Climate," U.S. Global Change Research Program, 19-67, 2014. Accessible at: *http://s3.amazonaws.com/nca2014/low/NCA3_Full_Report_02_Our_Changing_Climate_LowRes.pdf?download=1*.

An early step in identifying how DOTs can adapt their TSMO and maintenance programs is to identify possible entry points—existing decisions that could incorporate climate change considerations in the future. For example, knowing that there could be more frequent flooding events could change an agency's decision about what workforce capabilities are required for the season. Table 1 provides an example of potential TSMO and maintenance decisions which may be influenced by climate change and extreme weather. Additional examples and related information are provided in Appendix A – Matrix of Climate-Sensitive Decisions. For each decision, the appendix includes a description, how climate stressors affect the decision, and which climate stressors affect the decision.

Table 1. Example of Climate-Sensitive Decisions.

Climate-Sensitive Decision Areas	Specific Decisions	Description
1. Planning for future workforce needs.	Determine the right level of workforce requirements and capabilities.	Operating agencies make a variety of workforce-related decisions, including the number of staff required, their locations, and capabilities necessary to monitor, control, report, and maintain the roadway system.
2. Planning for operations and maintenance investments.	Determine criteria to prioritize operational resource investments (including capital improvements).	Resource investments may include new capital improvements for operations and maintenance such as control systems, field equipment, vehicles, communications, and power. They may also include investments for annual maintenance.
3. Budgeting for operations and maintenance.	Determine the appropriate funding needs and levels on annual and multi-year basis.	Operating agencies typically are funded on an annual basis. Funding levels greatly drive the overall program capabilities and functions.
4. Establishing realistic objectives.	Set regional operations objectives for the program.	Effective planning for operations requires a clear articulation of regional operations objectives. These objectives define the response strategies and the performance-based management required.

Note: Excerpted from Appendix A – Matrix of Climate-Sensitive Decisions.

While day-to-day management of traffic operations might not be particularly sensitive to broader changes in climate, the planning required to support agile TSMO and maintenance programs may involve more climate-sensitive decisions. For example, future workforce equipment needs, facility siting, material procurement, technology deployments, business processes, and institutional arrangements typically span multiple seasons and even years. The effectiveness of such decisions made today may be compromised by changes in climate.

The following list of questions can help agencies determine if a decision is climate-sensitive:

- Do climate variables have a direct effect on the decision outcomes? For example, will increases in precipitation overwhelm current maintenance practices?
- Can climate variables affect the underlying assumptions upon which the decision is founded? For example, will changes in the climate, such as precipitation, affect traffic levels, which in turn impact roadway operations and management?
- Is climate likely to change during the time period governed by the decision? Consider long-term, chronic changes in climate as well as the increased frequency of acute weather events.
    - What is the time horizon for planning and implementation?
    - How frequently is the decision made?

- Is this a single decision moment or a multiple decision moment (i.e., is the decision made once and then executed or is there room for refinement and adjustment over the course of implementation/operations)? Includes:
  - Financial reversibility (i.e., does the practice represent a cost that cannot be recovered?)
  - Foreclosure of other options (i.e., does implementing this practice limit the availability of other practices in the future?).

In addition, think about whether there are any specific weather thresholds at which the decisions become sensitive. Linking TSMO and maintenance practices to weather thresholds is a needed step in this process. To date, these rules have been ad-hoc and not formalized. In the past, experienced supervisors knew what activities could be scheduled based on weather conditions like precipitation, wind speeds, visibility, and temperature. There are no standard weather-related practices for maintenance or operations actions. When there are specific thresholds for weather conditions (e.g., staff cannot work without frequent breaks when temperatures are above X°F), projections on how those specific variables may change in the future can help inform planning.

Identifying Weather Sensitivity Thresholds

An important component of understanding how climate change may affect transportation systems management and operations (TSMO) and maintenance practices is understanding whether there are specific weather thresholds that affect TSMO and maintenance—and then, whether those thresholds may change in the future.

The links between weather, TSMO, and maintenance are often well understood at the individual level (e.g., maintenance supervisors), but these "rules" are often ad hoc and are rarely documented or formalized.

Consider using the climate change planning process to capture internal guidelines and weather thresholds. For example, the table below can serve as a "template" for identifying and recording weather sensitivity thresholds. This is derived for work focused on the Illinois and Iowa departments of transportation. The Capital Area Metropolitan Planning Organization (CAMPO) in Austin, Texas, completed a similar exercise to identify sensitivity thresholds as part of their Federal Highway Administration-funded Climate Resilience Pilot Project.

Table 2. Sample Template for Identifying and Recording Weather Sensitivity Thresholds.

TSMO/Maintenance Activity	Weather Variable	**Threshold** (conditions must be...)
Pavement maintenance: full depth concrete	Air temperature	≥ 50°F
	Relative humidity	≥ 60%
	Precipitation rate	≤ 0.01 in. hr.
	Probability of precipitation 3 hr.	≤ 40%
Pavement preventive maintenance: crack and joint sealing	Air temperature	30-60°F
	Precipitation rate	≤ 0.01 in. hr.
	Probability of precipitation 3 hr.	≤ 40%
Tree and shrub planting	24-hour precipitation	≤ 1 in.
	Precipitation rate	≤ 0.01 in. hr.
	Probability of precipitation 1 hr.	≤ 60%

Adapted from FHWA, Clarus Multi-State Regional Demonstrations, Evaluation of Use Case #3: Non-Winter Maintenance Decision Support System, "Appendix A," FHWA-JPO-11-118 (Washington, DC, 2011). Available from: *http://ntl.bts.gov/lib/43000/43100/43179/FHWA-JPO-11-118_Eval_Report_UC-3_FINAL.pdf*.

Additional information on possible impacts of climate change on transportation systems (including infrastructure and operations) can be found in Transportation Research Board (TRB) Special Report 290, National Cooperative Highway Research Program (NCHRP) Report 750, among others. This and other resources are available at the FHWA Virtual Adaptation Framework Climate Change Adaptation Case Studies and Resources.[18]

Using Scenario Planning to Understand Climate Change Vulnerability and Risk

Scenario planning is an approach to planning that is increasingly being used by transportation planning organizations to make critical decisions in the face of uncertainty. Scenario planning helps stakeholders answer questions such as what are the policies, strategies, or investments that help us achieve our goals in light of uncontrollable or unknown future conditions. Scenario planning brings together interagency and intra-agency stakeholders needed to effectively address an issue and helps them make decisions that are more robust in a variety of futures. It also helps create a more adaptive, resilient organization or program.

Scenario planning could be used to help make decisions regarding adapting a transportation systems management and operations (TSMO) or maintenance program for potential climate change impacts. Scenario planning allows organizations to explore several distinct possible futures that may result from different paths that climate change may take, analyze the potential consequences, and investigate alternative TSMO and maintenance strategies to address the issues. The scenario approach formalizes the consideration of uncertainty in preparing for climate change impacts in a systematic way. Scenario planning may also aid in helping to set expectations among planners and even the general public on acceptable levels of system performance under extreme conditions by assessing the trade-offs between levels of investment and levels of system operation during different levels of severe weather. Finally, the scenario process might also aid the region in better understanding its areas of susceptibility, thereby further helping to refine and strategically deploy TSMO and maintenance strategies.

There are models (e.g., Maintenance Decision Support System [MDSS]; Sea, Lake, and Overland Surges from Hurricanes [SLOSH]) that can be can be used to run extreme future event scenarios. These model runs could be used to inform a planning process that considers high heat, winter storms, summer storms, sea level rise, wildfires, or cascading impacts (e.g., power/utility failure, landslides).

D. Assess Vulnerability

The level of vulnerability assessment needed – high-level or detailed, qualitative or quantitative, statewide or localized, agency-wide or by departments – will vary based on the types of decisions required. Regardless of the exact process used, the following are key elements of a vulnerability assessment.

1. Document Existing Capabilities

It is important to take a look at current or baseline capabilities (assessing both technical as well as institutional capability to respond to climate and extreme weather) before seeking to determine improvements in those capabilities (discussed in Section III.E.4). The CMF provides a useful framework for assessing and documenting existing institutional capabilities (and will be discussed again later in the context of determining improvement in capabilities necessary for successful implementation of adaptation measures). The framework defines capability in terms of six areas that together inform the agency's overall ability to respond to changing conditions: business processes, systems and technology, performance management, culture, organization and workforce, and collaboration. Documenting current capabilities and identifying where those capabilities fall on the spectrum of ad-hoc implementation to planning for

18 U.S. Department of Transportation, FHWA, FHWA Virtual Adaptation Framework Climate Change Adaptation Case Studies and Resources. Available at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/resources/index.cfm*.

optimized practices will help an agency gain a better sense of how resilient they may already be to climate change and extreme weather events.

2. Collect and Integrate Data on Past Performance

Examining previous vulnerabilities can be an excellent starting point for thinking about future vulnerabilities. Common climate change-related TSMO and maintenance program vulnerabilities include:

- Loss of roadway capacity.
- Loss of alternative routes.
- Loss of situational awareness (due to power/communication).
- Inability to evacuate/shelter-in-place.
- Loss of service life (due to faster deterioration, etc.).
- Increased safety risk.
- Loss of economic productivity.
- Reduced mobility.

Internal records or other data on how the system has fared during previous extreme weather events can provide a rich source of insights into potential future vulnerabilities. Any of the following could be a source of information about system vulnerabilities:

- **Traffic incident reports** – Check whether there were any incidents during specific recent extreme weather events that correspond to the climate stressors under evaluation (e.g., heat waves, heavy rain events, tropical storms).
- **Maintenance records** – Check maintenance records for the time surrounding specific recent weather events.
- **After-action reports** –These reports, compiled after extreme weather events, describe what happened, why, and areas for improvement. Mine these reports for information about vulnerabilities for applicable weather events.
- **Emergency reimbursement forms** – For declared disasters relevant to the climate stressors under evaluation, review Federal Emergency Management Administration (FEMA) or other emergency reimbursement requests to identify the magnitude and scope of damages during past events.
- **Staff interviews across departments** – On-the-ground staff at DOTs often have deep institutional knowledge about existing vulnerabilities that may not be well-documented. Asking staff “What keeps you up at night?” can help facilitate discussion about key system vulnerabilities.[19]

Mining Agency Institutional Knowledge for Vulnerability Assessments

Washington State DOT (WSDOT) completed a statewide climate change vulnerability assessment in 2011. Their vulnerability assessment focused on asset-level vulnerabilities, but the approach would be transferrable to transportation systems management and operations (TSMO) and maintenance vulnerabilities. The WSDOT assessment relied on a series of workshops with WSDOT staff, including district maintenance supervisors and their staff. They asked “What keeps you up at night?” and had staff individually rate each asset’s vulnerability on a scale of 1 to 10. Lower scores corresponded to reduced capacity or temporary operational failure, while higher scores corresponded to complete asset failure.

Reference: WSDOT, Climate Impacts Vulnerability Assessment Report, November 2011. Available at: *http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf*.

19 WSDOT, Climate Impacts Vulnerability Assessment Report, November 2011. Available at: *http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf*.

If possible, build a dataset to correlate past extreme weather disruptions—gathered from the above sources—with information on the weather conditions associated with the event.

Local National Weather Service (NWS) Forecast Offices (there are 122 nationwide) house "Weather Event Archives" that can be very useful sources of information on past extreme events.[20] It is also important to share collected information across offices or departments.

Getting Started: Strategies for Documenting Institutional Knowledge

On-the-ground staff at departments of transportation (DOTs) are largely aware of the current weather-related problems they face on a regular basis. In addition, they are valuable resources in discussing hypothetical extreme weather scenarios, and may be able to readily identify potential points of failure.

Below are several possible mechanisms to collect and document the valuable institutional knowledge of staff, which can then be leveraged to improve planning for transportation systems management and operations (TMSO) and maintenance in the face of climate change.

- Conduct interviews with staff to document their knowledge of vulnerabilities. Interview questions can include:
  - Recall [a recent severe weather event]. How did that affect your purview?
  - When you have advance warning of an extreme [summer storm/winter storm/hurricane/heat event]:
    - What responses are triggered? Are those responses tied to any thresholds in event severity (e.g., only if there is more than 3" of snow)?
    - What personnel are involved?
    - What contractors are put on notice in the preparations?
    - What materials and equipment are put on standby?
  - When the event is over:
    - What inspections/audits are conducted to evaluate impacts?
    - How are corrective actions planned?
- In a workshop setting, have staff place pins or dots on a map of the transportation system to identify locations with frequent weather-related issues (e.g., flooding, potholes).
- Establish regular debriefs to bring together the department's cross-cutting (or multi-disciplinary) teams to discuss weather-related issues. Designate a person to take notes during the meeting and write down what works well, what does not, and what needs to change to make the system more resilient.
- Establish transition plans for retiring staff. Ask them to write down their regular duties, habits, and unwritten expertise.

3. Develop Climate Inputs

In addition to gathering information on past weather disruptions and identifying key TSMO and maintenance weather sensitivities, another important component of a climate change vulnerability assessment is collecting data, qualitative or quantitative, on how climate stressors are projected to change locally. The focus should be on identifying how specific weather thresholds identified as currently affecting TSMO and maintenance activities may change in the future.

20 Historical Weather Event Archives are not always easy to find on NWS Regional Forecast Office web pages, but are usually housed under the Climate section.

Several sources exist to provide information on potential future climate changes, a selection of which are highlighted in the following text box. See Module 4 of the FHWA Framework[21] for additional guidance on gathering climate inputs.

Sources for Climate Inputs

Table 3. Sources for Climate Inputs.

Resource	Description
National Climate Assessment *http://nca2014.globalchange.gov/*	• High-level descriptions of how climate stressor may change. • Focused on larger geographic areas. • Good starting point to identify what types of climate changes are expected in the region.
United States Department of Transportation Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool *http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/*	• Excel-based tool to provide projections for climate variables relevant to transportation planners (e.g., number of days above 95°F, hottest 7-day temperatures, largest 3-day precipitation events). • Local-scale (56-224 sq. miles).
U.S. Climate Resilience Toolkit *https://toolkit.climate.gov/*	• Evolving national "one-stop-shop" for climate information. • Provides links to dozens of climate projection data sources.
State Climatologist	• May have already developed projections of how climate may change in the state/region.
University Climate Research Centers	• May have already developed projections of how climate may change in the state/region.

For additional information, see the "Develop Climate Inputs" section of the Federal Highway Administration Virtual Framework at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules/index.cfm?moduleid=4*.

In addition to collecting information on climate projections, many transportation agencies have found it helpful to collect information on historical weather conditions in order to provide context for the projections. Examine Road Weather Information System (RWIS) data to help establish the climate record for the area. All properly sited and maintained weather stations can be a vital part of the climate record, especially if they have been maintained for longer than 30 years. If RWIS data is not available, data can be obtained from the local weather station(s) through the National Weather Service.

21 U.S. Department of Transportation, FHWA Virtual Adaptation Framework. Available at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules/index.cfm?moduleid=4*.

Understanding Uncertainty

Future climate change is dependent upon the amount of global greenhouse gasses emitted. In the near term, it is easier to predict emission levels because they will likely be similar to today's rate of emissions production given the limited time for society to evolve. It is very difficult to project emission levels out 50 to 90 years into the future because it is not known how our global society will evolve over time (e.g., population growth, economic growth, energy use, development of significant technological advancements, political action mitigating emissions). Thus, the range of plausible future emissions expands over future time, along with the plausible range of climate responses.

Figure 9. Diagram. Increase in Uncertainty Over Time.

Near term climate projections have a tighter range of possibilities, while distant climate projections have wider range of possibilities.

Any projections of future climate conditions are subject to this uncertainty, but that doesn't have to prevent agencies from using this information. Scenario planning exercises can help departments of transportation identify adaptation strategies that increase resilience in a range of potential future conditions (see text box on page 23).

4. Characterize Impacts and Risks

Synthesize information on potential climate changes, past impacts, and known sensitivities to characterize possible impacts of climate change on TSMO and maintenance programs.

Determine Outputs

Think about how results will be used to determine what level of information is needed to inform decisions. Options include:

- **Qualitative vulnerability ratings** of individual decisions, functions, components, or locations (the level of detail decided at the outset) – e.g., High, Medium, Low vulnerabilities. In this approach, consider vulnerability as a function of three components:[22]
  - **Exposure** – The nature and degree to which a system or asset is exposed to significant climate variations (i.e., whether and how climate stressors will change).
  - **Sensitivity** – Degree to which an asset or system is affected by exposure (i.e., if all assets were equally exposed, which would experience the greatest damage?).
  - **Adaptive Capacity** – Ability of a system to adjust, repair, and respond to damage or disruption. Adaptive capacity may not be applicable or ratable in many cases, so it may be excluded from vulnerability assessments.

Figure 10 provides an example of a rapid qualitative assessment of the vulnerability of a pavement maintenance program to increasing temperatures. It assumes that no information is readily available on adaptive capacity for this rapid assessment (i.e., that more information might need to be gathered to assess that component if a more detailed assessment is determined to be useful).

22 U.S. Department of Transportation, U.S. DOT Gulf Coast Study, Phase 2, "*Task 3.1: Screen for Vulnerability*," FHWA-HEP-15-019 (Washington, DC, 2014). Available at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/case_studies/gulf_coast_study/engineering_and_tasks/task31.pdf*.

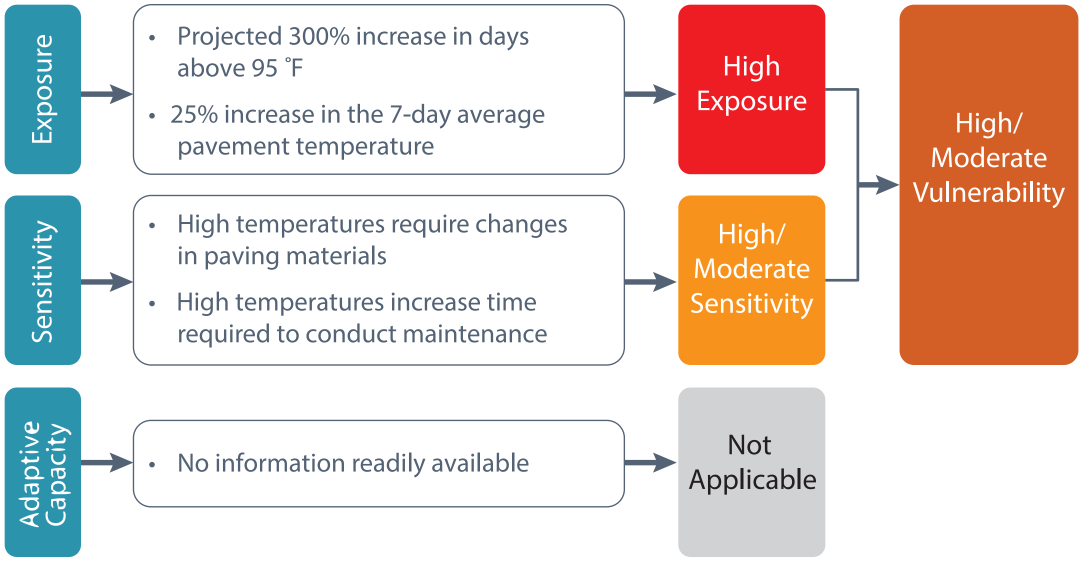

Figure 10. Diagram. Rapid Qualitative Assessment of the Vulnerability of Pavement Maintenance Program to Extreme Heat.

- **Quantitative vulnerability ratings** – Use a quantitative approach to assign vulnerability ratings based on exposure, sensitivity, and adaptive capacity. For example, define and quantify sensitivity in terms of potential impact (e.g., costs, delays, disruptions).
- **Qualitative risk ratings –**Identify "risks" rather than "vulnerabilities." The concepts are similar, but risk is different in that it incorporates likelihood of potential impact.
  - Risk is traditionally defined as the product of likelihood and consequence. Likelihood is parallel to the exposure component of vulnerability, and consequence is parallel to sensitivity.
  - Likelihood of potential impacts can be very difficult to evaluate, given the uncertainties inherent in climate projections. However, some agencies are more familiar with the concept of "risk" than vulnerabilities, so choose to present risk ratings.
- **Quantitative risk ratings** – Use a quantitative approach to calculate risk of impacts.

Determine Approach

Regardless of the intended outputs, there are three primary options for how to determine those outputs.

- **Data-driven, desktop analysis** – Compile and assess data on climate projections and past impacts of weather events to determine future impacts of climate change.
- **Workshop-based, stakeholder-driven analysis** – Engage staff and other stakeholders to qualitatively assess vulnerabilities or risks. For example, ask staff to identify the locations most susceptible to flooding, or the hypothetical consequences of different climate scenarios.
- **Hybrid approach** – Complete a desktop analysis with available data, and "ground truth" the results with stakeholders through workshops, one-on-one interviews, or other mechanisms to get their feedback.

See the "Getting Started" boxes below for checklists to follow, along with tools and materials to evaluate climate change vulnerabilities or risks.

Getting Started: Transportation Systems Management and Operations (TMSO) and Maintenance Vulnerability/Risk Assessment Matrix

This matrix lays out the possible areas to assess for vulnerabilities. It can be used as a "checklist" (i.e., check off each cell as it is completed), or to house assessment results (i.e., enter High, Medium, Low, or Not Applicable for each cell).

Example Vulnerability Assessment Matrix – Catalog of the Potential Areas where TSMO, Maintenance, and Emergency Management Functions May be Vulnerable

In each cell, rate vulnerabilities as High, Moderate-High, Low-Moderate, Low, or Not Applicable (row and column headings are intended to be illustrative rather than comprehensive).

Table 4. Example Vulnerability Assessment Matrix.

	Extreme heat, temperature increases	Heavy rain events	Flooding	Storm surge	Sea level rise	Drought	Wildfire	Winter storms	Changes in freeze/thaw cycles	Permafrost thaw
TSMO Functions										
Emergency response protocols										
Pre-deployment of emergency supplies and equipment										
Use of intelligent transportation systems (ITS)										
Procedures for road/bridge closures										
Incident management										
Road weather management										
Asset management										
Freeway and corridor management										
Arterial management										
Maintenance Functions										
Bridge maintenance										
Pavement maintenance										
Shoulder maintenance										
Embankment maintenance										
Culvert maintenance										
Vegetation management										
Signage										
Crew scheduling										
Drainage clearing										
Fencing										
Painting										
Emergency Management Functions										
Planning										
Mitigation										
Response										
Recovery										

Getting Started: Desktop Vulnerability/Risk Assessment Checklist

- □ Determine desired outcome of vulnerability/risk assessment – vulnerability vs. risk, qualitative vs. quantitative.
- □ Identify "wish list" of projected climate data (based on what climate impacts are relevant).
- □ Collect historical climate data for those variables/event types.
  - Possible sources include Road Weather Information Systems (RWIS), National Weather Service, agency weather data providers.
- □ Collect data on projected changes in those variables/event types.
  - See Federal Highway Administration (FHWA) Virtual Framework for data sources.
- □ Collect data on historical impacts of events – costs, delays, disruptions, etc.
  - If requesting data from others within the organization, provide templates to make it easier for them to provide the requested data.
- □ For each component under evaluation, determine its Exposure (e.g., potential change in temperature, whether it would be flooded under certain scenarios), Sensitivity, and Adaptive Capacity.
- □ Use qualitative or quantitative methods to derive a vulnerability rating based on exposure, sensitivity, and adaptive capacity ratings for each component.
  - For qualitative methods, see "Vulnerability Rating Exercise" below.

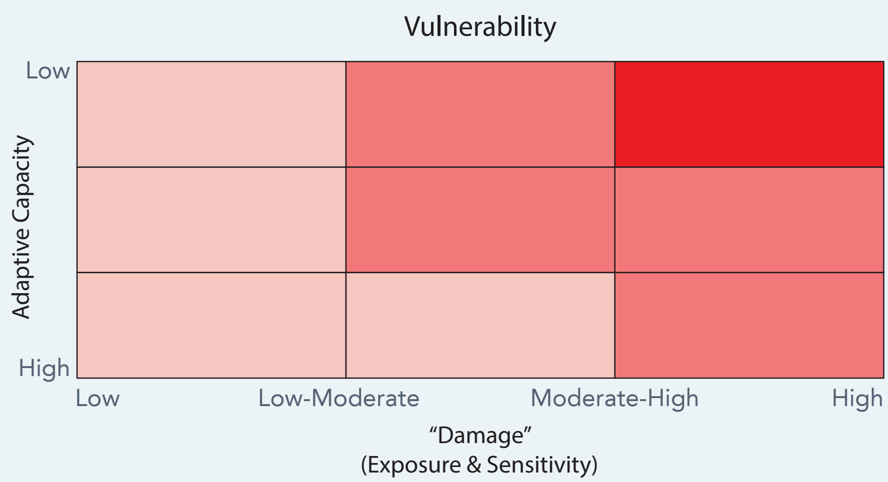

Figure 11. Graph. Vulnerability as a Function of Adaptive Capacity and Damage.

- □ Or a Risk rating based on event likelihood and consequence for each component.
- □ For qualitative methods, see "Risk Rating Exercise" below.

Getting Started: Desktop Vulnerability/Risk Assessment Checklist (Continued)

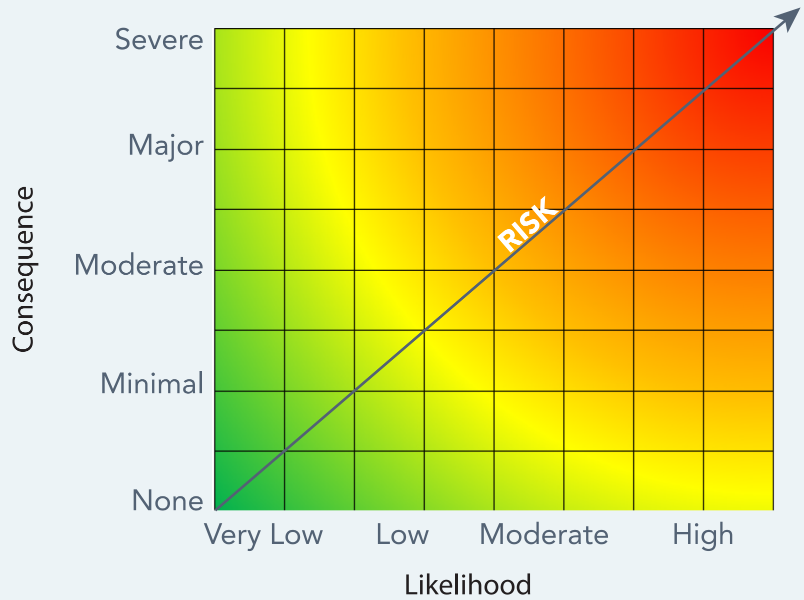

Figure 12. Graph. Risk Shown as a Function of Consequence and Likelihood.

- ☐ Engage on-the-ground staff across departments to review and vet the results.
- ☐ Refine results as needed.
- ☐ Revisit results over time.

Getting Started: Workshop-Based Vulnerability Assessment Checklist

- ☐ Identify stakeholders to participate in the vulnerability assessment process. Candidates include:
  - Regional/district maintenance supervisors and staff.
  - Planning department staff.
  - TSMO staff.
  - Materials engineers.
  - Emergency management staff.
  - Asset management staff.
  - Geographic information system (GIS) staff.
  - Regional partners (e.g., neighboring State departments of transportation (DOTs), metropolitan planning organizations (MPOs), corridor management organizations).
  - Federal and local partners (Federal Highway Administration (FHWA), local DOTs, transit operators).
  - Private sector partners (freight carriers, regional bus operators (e.g., Greyhound).
- ☐ Define a clear scope and objectives for the workshop(s) and set an agenda.
  - Example agenda:
    - Introductions.
    - Review of potential climate changes and impacts of those changes.
    - Discussion: potential impacts of projected changes.
    - Review of available data (impacts of past events, historical trends).
    - Discussion/breakout groups oriented to achieve workshop goal (e.g., vulnerability ratings for each component; identification of critical areas, priorities for future research; discussion of available data?).
    - Next Steps.
    - Wrap Up.
- ☐ Develop background materials for workshop (see sample handout in Appendix E. Sample Handout for Workshop on Climate Change Risk).
  - Collect available information.
  - Identify recent extreme weather events to spark discussion.
  - Compile information on projected climate changes. See FHWA Virtual Framework for data sources.
- ☐ Hold workshop.
- ☐ Distribute follow-up items as needed.

Washington State DOT (WSDOT) Vulnerability Assessment Workshops

WSDOT identified a strategic goal to "identify WSDOT facilities vulnerable to the effects of climate change and to evaluate and identify possible strategies to reduce risk." As part of an FHWA pilot program, WSDOT developed a structured, stakeholder-based approach to qualitatively assess facility risk. The project team held 14 workshops in all regions of the state in which WSDOT staff rated all State-owned highways and other transportation assets for climate vulnerability. In the workshops, participants used asset maps, climate scenarios, and their local knowledge to assess vulnerability.

At the start of each workshop, the project team presented a video about climate impacts on infrastructure, climate change scenarios for the state, and impact maps. A GIS specialist was on hand to overlay detailed asset inventories with climate impact data. Workshop participants then used a qualitative scoring system to assess roadway segments (or other assets) for criticality and to rate the effect that projected changes in climate would have on WSDOT infrastructure.

The total number of workshop participants exceeded 200, including maintenance staff; regional office staff; and state ferry, aviation, and rail system managers.

Additional information on the WSDOT vulnerability assessment approach is available at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/resources/washington_state/.

E. Integrate into Decision Making

1. Identify Performance Measures

Performance measurement can help to measure qualitative and quantitative progress towards meeting the objectives of TSMO and maintenance programs. Performance measures can also help decision makers in determining how to spend their limited budgets by focusing expenditures towards specific operational issues in order to help them improve their performance metric scoring. Many DOTs have adopted or are in the process of developing performance measures.[23] If a DOT desires to become more resilient to the impacts of climate change, it is important to integrate that desire into performance measures to ensure that progress toward that goal is tracked over time.

The concept of climate change adaptation and resiliency can either be integrated into existing performance measures or adopted as a stand-alone measure. Good measures are defined in part by their ability to be measurable, understandable, and meaningful.[24]

Integrating Climate Change into Existing Objectives

Florida Department of Transportation's 2060 Florida Transportation Plan outlines six overarching goals: (1) Economic Competitiveness, (2) Community Livability, (3) Environmental Stewardship, (4) Safety and Security, (5) Maintenance and Operations, and (6) Mobility and Connectivity. Within each goal, the plan sets specific objectives. Under the fifth goal, "Maintain and operate Florida's transportation system proactively," one of four objectives is "Reduce the vulnerability and increase the resilience of critical infrastructure to the impacts of climate trends and events." The plan outlines implementation strategies and performance indicators for the goal.

DOTs should consider whether revisions to existing performance measures are necessary to accommodate climate change. When setting or revising performance measures, it is important to work with local communities to establish a tolerance level for disruption (i.e., the acceptable level of operational performance if threat occurs) given the changes that are projected to occur due to climate change. It will be critical to explain that in some ways TSMO objectives may become easier while in other ways it may become harder (e.g., increased frequency and intensity of storm events). By using a scenario planning process, it can be demonstrated that in some instances, it will be harder to maintain historic levels of service (LOS) with more intense/frequent events and therefore the performance measures may need to be revised to reflect the changing reality. During this outreach process, it will also be valuable to discuss the public's mounting expectations for faster responses and constant access to a highly operational roadway system in order to emphasize the need to reach a common understanding of reasonable levels of service during extreme weather events.

23 The FHWA Office of Operations has prepared multiple resources for agencies looking to develop and track performance measurement that are relevant to TSMO. There resources are available at: *http://www.ops.fhwa.dot.gov/perf_measurement/*.

24 FHWA Operations Performance Measurement Fundamentals. Available at: *http://www.ops.fhwa.dot.gov/perf_measurement/fundamentals/purpose.htm*.

Getting Started: Climate Change Focused Performance Measures

The table below contains a sample of operations objectives and performance measures that could be adopted by an organization looking to improve weather-related operations. These objectives and measures can also be used to focus a program on improving preparation and response to the impacts of climate change.

Table 5. Sample Operations Objectives and Performance Measures.[25]

Category	Operations Objectives	Performance Measures
Clearance Time (Weather-Related Debris)	• Reduce average time to complete clearing (mode, hierarchy of facilities, or subarea of region) of weather-related debris after weather impact by X percent in Y years. • Reduce average time to complete clearing (interstates, freeways, expressways, all roads, main tracks, and main sidewalks) of weather-related debris after weather impact by X percent in Y years.	• Average time to clear selected surface transportation facilities of weather-related debris after weather impact.
Detours for Impacted Roadways	• Increase by X percent the number of significant travel routes covered by weather-related diversion plans by year Y. • Increase the percentage of agencies that have adopted multi-agency weather-related transportation operations plans and that are involved in transportation operations during weather events to X percent by year Y.	• Percentage of significant travel routes covered by weather-related diversion plans. • Percentage of agencies involved in transportation operations during weather events that have adopted multi-agency, weather-related transportation operations plans.
Disseminating Information	• Reduce time to alert travelers of travel weather impacts (using variable message signs, 511, Road Weather Information Systems [RWIS], public information broadcasts, the agency's website, Web 2.0 technologies, etc.) by X (time period or percent) in Y years.	• Time from beginning of weather event to posting of traveler information on (variable message signs, 511, RWIS, public information broadcasts, etc.). • Time from beginning of weather event to posting of traveler information on agency website.
Road Weather Information System Coverage	• Increase the percentage of major road network (or transit network or regional bicycle network) covered by weather sensors or an RWIS by X percent in Y years as defined by an RWIS station within Z miles.	• Percentage of major road (transit or bicycle) network within Z miles of an RWIS station.
Signal Timing Plans	• Special timing plans are available for use during inclement weather conditions for X miles of arterials in the region by year Y.	• Number of miles of arterials that have at least one special timing plan for inclement weather events.

25 U.S. Department of Transportation, FHWA and Federal Transit Administration, *Advancing Metropolitan Planning for Operations: The Building Blocks of a Model Transportation Plan Incorporating Operations - A Desk Reference,* April 2010. Available at: http://www.ops.fhwa.dot.gov/publications/fhwahop10027/index.htm.

2. Identify Potential Adaptation Measures

Adaptation strategies should be developed to address known vulnerabilities directly—either those already experienced or those identified through a vulnerability assessment. By mapping the strategies to the vulnerabilities, there is a direct link from problem to solution. Additionally, the strategies should be developed to help achieve new or existing performance metrics.

Frequently, adaptation strategies can be identified by looking to best practices in other states or regions that already experience more severe weather events. While the South may not be used to responding to ice storms, their counterparts in the North can provide guidance on how to prepare for, respond to, and recover from this type of event. This "climate shifting" is also true for extreme heat waves, flooding, landslides, wildfires, and other climate stressors. To develop strategies, review examples and best practices from other agencies and engage a diverse range of staff within the organization. The staff with longer tenures frequently knows the issues that arise during extreme weather events and can identify solutions to the problems.

Best Practices from the Field	
Alaska	The Alaska Department of Transportation & Public Facilities (ADOT&PF) is now conducting anti-icing with salt brine in the City of Fairbanks and other parts of interior Alaska. Historically, Fairbanks and interior roads would stay frozen from mid-fall to late spring, but now thawing and freezing rain events have caused the ADOT&PF to perform anti-icing, something never considered previously in the interior.
Washington	Washington State Department of Transportation (WSDOT) recently invested in improvements to wireless communications capabilities and communication redundancies between traffic management centers (TMCs). The agency also filled in communication gaps to ensure continuous communication across rural areas in the event of an emergency.
Maryland	Maryland State Highway Administration (MDSHA) has installed backup power supply to three-quarters of its cameras and will have complete coverage by the middle of 2015. The situational awareness gained through closed-circuit televisions (CCTVs) is critical for maintaining public safety during severe weather. MDSHA also has back-up power on traffic signals to avoid manual traffic direction.
New York, New Jersey, Connecticut	State and local member organizations rely on the Transportation Operations Coordinating Committee (TRANSCOM) regional coordinating body to lead multi-agency coordination and communications, particularly during incidents or weather events. The organization has developed redundant (duplicate and triplicate) data servers and networks to ensure its information sharing systems can operate during an extreme event such as Hurricane Sandy, even in case of power outages. TRANSCOM has two server rooms and two server feeds within its offices, a backup in New Jersey, and a disaster recovery site on the west coast.
Alaska	ADOT&PF issued a policy directive on winter maintenance coordination that requires all regions in the agency to assist in the event of an emergency, regardless of location. Likewise, WSDOT effectively dissolves district lines within the organization when responding to major events so that resources can be applied where they are most needed across the state.
Minnesota	The maintenance division for Minnesota DOT (MnDOT) recently began working more closely with the transportation operations centers (TOCs) to ensure that the TOCs are fully utilizing the MnDOT road weather technology programs to help meet the organization's common goal of serving the needs of the freight, transit, and traveling public communities.

Best Practices from the Field (Continued)	
Wyoming and Utah	Both the Wyoming DOT and the Utah DOT have citizen reporting programs that allow travelers to report back to the DOT on road conditions. This expands the DOT's awareness of hazardous road conditions on the network and helps the DOT provide "fresher" traveler information to the public. The Utah DOT uses the nation's first road weather reporting smartphone application.
Multiple States	The FHWA Integrated Mobile Observations demonstration project involving multiple States, including MnDOT and Michigan DOT (MDOT), is a technological advancement that aims at improving resilience to extreme events. By using mobile data of atmospheric conditions around the vehicles, operations and maintenance supervisors can use real-time information to inform decisions about workforce deployment, road closures, or appropriate treatments to use. The data will eventually be pushed to connected vehicles for in-vehicle alerts.
Washington	Responding to more intense and frequent weather events requires additional staff. WSDOT has recently begun using the National Guard when necessary for transportation-related activities. They act as an extension of WSDOT and the Washington State Patrol in assisting with road closures. WSDOT has found it important to know which external resources are available (e.g., National Guard), what roles those resources can serve, and how to access those resources quickly.

It is important to consider a diverse range of adaptation strategies to ensure that possible solutions, easy and difficult, are considered. Strategies for TSMO and maintenance should include the following types:

- **Policy-based changes** – including guidance on incorporating climate change adaptation in TSMO and maintenance programs.
- **Built infrastructure measures** – including construction of protective barriers, infrastructure hardening, permanent or temporary infrastructure relocation, development of climate-resilient design standards and retrofits, and green infrastructure.
- **Operational approaches** – promote avoidance or reduction of impacts, as well as rapid and effective response to impacts as they occur.
- **Adaptive management** – tracks hazards, impacts, costs, and effectiveness of adaptations and post-disaster response to inform the aforementioned categories of adaptation. This type of disciplined tracking of climate or weather impacts serves as an interim adaptation strategy to help both determine whether and what adaptation actions are necessary as well as develop a quantitative basis for investments and/or reimbursements. RWIS can be an important tool in tracking road weather conditions over time, anticipating maintenance needs, and identifying areas in need of investment.

Table 6 provides examples of some phased adaptation strategies that agencies may wish to consider. Before selecting any strategies, agencies should understand their own vulnerabilities and undertake a more robust and location-specific adaptation strategy development process.

Table 6. Sample Adaptation Strategies and Time Frames.

Vulnerability	Response	Implementing Department
Increased frequency of extreme events may require additional personnel to monitor, control, report, and respond to events. Changes in long-term climate trends may also change seasonal work requirements (e.g., changes in winter weather seasons, construction timing, or landscaping timing) and necessitate additional or unique staff expertise to monitor and respond to new types of climate events (e.g., snow storm in Atlanta).	**Short-term:** Train existing personnel on the potential impacts of climate change and how this may affect their roles and responsibilities. **Medium-term:** Increase the availability of contract staff to assist during extreme events. Develop memorandums of understanding (MOUs) with other agencies for equipment and staff sharing during extreme weather events. **Long-term:** Hire additional staff to keep pace with increasing transportation systems management and operations (TSMO), maintenance, and emergency management needs.	TSMO, Maintenance, Emergency Management
Extreme events and long-term changes in climate can affect resource requirements. For example, increases in temperature can increase annual pavement maintenance costs, or changes in freeze/thaw cycles can increase potholes. Changes in winter weather and increasing weather uncertainty could also affect budgets.	**Short-term:** Increase cost tracking to respond to specific extreme weather events (see Getting Started: Data Collection Best Practices). Establish a "rainy-day" fund for unexpectedly bad years. **Medium-term**: Revise budgeting process and protocols to account for recent trends that may diverge from the historical baseline. **Long-term:** Work with meteorologists and climatologists to develop a process for taking anticipated future events into account while budgeting and planning.	Maintenance
Siting equipment in areas that will be impacted by sea level rise, ecological damage, flooding, snowfall, or other climatic events may damage the infrastructure.	**Short-term**: Consider Federal Emergency Management Agency (FEMA) flood zone maps (after confirming the relevant local maps are up to date) or other similarly informative maps when siting and designing sites for equipment. **Medium-term:** Include consideration of future stressors (e.g., accelerated sea level rise) when making decisions about siting equipment. Consider changes (e.g., increasing freeboard requirements) to accommodate more intense rainfall events. **Long-term:** Shift investments to mobile data sources (e.g., citizen reporters, snow patrol reporting, mobile probes), which are less likely to end up in harm's way.	TSMO, Maintenance

Table 6. Sample Adaptation Strategies and Time Frames (Continued).

Vulnerability	Response	Implementing Department
Climate stressors can lead to increased asset deterioration, requiring more frequent inspections (which can be expensive and time consuming).	**Short-term:** Track impacts of weather events in order to identify "hot-spots" that may require an increased rate of inspection. **Long-term**: Use detailed, downscaled climate models to determine portions of the state (or region) that are anticipated to have greater shifts in climate. Dedicate increased inspection resources to those areas.	Maintenance
Pavements are designed to withstand particular temperature thresholds. High temperatures may lead to rutting, while cold (and freezing) conditions increase potholes.	**Short-term**: Increase inspection and tracking of roadway conditions. **Medium-term:** Assess downscaled projected changes in temperatures to determine if a change in the pavement mix may be required. **Long-term**: When repaving occurs, adjust paving mix as needed. Consider utilizing cooler pavements (e.g., light-colored aggregate) to reduce surface temperatures.	Maintenance
Increased frequency of precipitation (especially extreme precipitation), and increased high heat days may decrease worker safety and require delays in construction. Certain elements of construction (e.g., laying concrete, painting roads) can only be accomplished during a narrow range of weather conditions. Changes in weather will impact the length of the construction season and the contracts with construction companies.	**Short-term:** Continue current worker safety and project-bid practices. **Medium-term:** Expand the use of technologies for pavement placing that operate better under high temperatures, for example, cold-in-place recycling, coarser aggregate, or using ice or chilled water to cool the asphalt. Investigate other technologies that are suited to faster construction during adverse weather conditions. **Long-term:** Consider revising the construction season to start earlier and end later due to increased temperatures. During the height of summer, shift construction work to early morning and evening hours.	Maintenance
Increased rain (in some parts of the country) paired with increased temperatures can lead to accelerated vegetation growth and death. The dry fuel that remains poses wildfire hazards.	**Short-term**: Increase vegetation control within existing right-of-way. **Medium-term:** Plant more drought tolerant vegetation that is less likely to provide fuel for wildfires. *Often deferred due to resource constraints, effective decisions in this area may in fact be more critical to operational capability than anticipated.*	Maintenance

Table 6. Sample Adaptation Strategies and Time Frames (Continued).

Vulnerability	Response	Implementing Department
Flooding or other extreme weather may cause long-term disruptions to traffic (that run counter to current understanding of demand-supply relationships in a system).	**Medium-term**: Develop a plan for maintenance of traffic during weather events of various intensities (including non-severe, recurrent weather). In some cases, this may require significant detours and wide area communications to support adequate traveler information. Develop plans for culvert clearing and other maintenance or asset management activities. **Long-term:** Create after-event reports that assess what worked and what did not. Revise plans based on lessons learned.	TSMO, Maintenance

3. Evaluate and Select Adaptation Measures

As with all transportation budgeting processes, it is unlikely that DOTs will be able to fund their entire "wish-list" of adaptation strategies. In order to narrow the list of strategies to a prioritized list, it is useful to use a systematic evaluation process.

San Francisco Bay Area Metropolitan Transportation Commission (MTC)

In the development of its Adapting to Rising Tides study, the MTC used a series of steps to evaluate and narrow the list of potential adaptation strategies. Using a screening exercise followed by a qualitative assessment, the project team selected five strategies for further development.

The screening exercise included questions on the scale and replicability of the strategy, the barriers to implementation, the urgency of action, and impacts on society/equity, environment, and economy.

The qualitative assessment used an ordinal ranking system to compare the financial, social, environmental, and governance-related (e.g., funding, legal barriers) performance of the strategies.

As a last level of review, the project team used its professional experience to select a final set of balanced strategies.

The final report, with documentation of the adaptation action selection process, can be found here: http://files.mtc.ca.gov/pdf/MTC_ClmteChng_ExtrmWthr_Adtpn_Report_Final.pdf.

Some agencies may have established evaluation criteria for projects through other processes; if so, a variation on those criteria may prove to be an effective communication tool. If no such criteria exist, the following criteria may provide a useful starting point:

- **Technical and Political Feasibility** – how practical it is for a particular strategy to be implemented, accounting for engineering, policy, legal, and insurance considerations?
- **Cost and Benefits** – what are the up-front costs of implementation and the ongoing operations and maintenance costs? If implemented, what is the value of the damages from climate change that would be avoided?

- **Efficacy** – if implemented, to what extent would the strategy reduce the risk?
- **Flexibility** – if implemented, how easy would it be to revise the strategy at a later date? What is the adaptive management potential of the strategy?
- **Sustainability** – does the strategy advance the "triple bottom line" of sustainability (e.g., what are the impacts to the economy, society, and the environment)?[26]

Co-Benefits of Adapting

Departments of transportation (DOTs) should identify and account for the benefits and co-benefits of integrating specific adaptation strategies into transportation systems management and operations (TSMO) programs. Generally, co-benefits are assessed at a qualitative level in order to help identify "win-win" strategies that increase resiliency to climate change and help to achieve other program objectives. Often, it is easier to obtain support for funding these types of solutions because they accomplish multiple goals. For example, several DOTs have justified upsizing culverts by highlighting the benefits for fish passage in addition to the increased capacity provided for increases in extreme precipitation events.

Some examples of co-benefits include:

- Greenhouse gas mitigation.
- Decreased operating costs.
- Increased roadway safety.
- Sustainability (i.e., improvements to the economy, environment, or social equity).
- Improvements in other performance measures.

Depending on the needs of the DOT, the evaluation can be qualitative or quantitative in nature. A qualitative evaluation process is generally sufficient for selecting priorities while a quantified evaluation may be necessary in order to justify funding. A qualitative evaluation may use a simple three point or five point scale (e.g., low, medium, high or positive, neutral, negative) or rely on a narrative description of the pros and cons of the strategies. A quantitative evaluation can be more effective when competing for funding because it enables an agency to show hard numbers about the benefits of the program. Additionally, quantitative evaluation metrics (e.g., reduction in traffic delay) can be translated into financial benefits to be used in an economic assessment of the strategy. In some cases, as with FEMA Hazard Mitigation Funding, it is required to demonstrate the cost effectiveness of adaptation strategies before they will be funded. For more information on cost effectiveness tools and resources, see the Additional Resources section of this document.

While evaluation metrics are a useful tool for informing the decision making process, they should not be the basis for the entire decision making process. The input of the staff who work on these programs on a daily basis and of the decision makers who understand the needs of the community are also important pieces of information to take into account during the strategy selection process. Additionally, it is recommended that the total number of evaluation measures be kept to a small set of valued measures in order to allow for the output to be digestible and meaningful.

26 In October of 2012, FHWA launched INVEST 1.0 (Infrastructure Voluntary Evaluation Sustainability Tool), a web-based tool that helps transportation agencies incorporate sustainability considerations into their transportation programs and projects. The tool contains a module focused on operations and maintenance that enables agencies to self-assess their operations and maintenance activities with regard to sustainability. The tool is available online at: *https://www.sustainablehighways.org*.

Consider Implementation Time Frames in Prioritizing Strategies

Prioritize adaptation measures into short-term (0-5 years), medium-term (5-10 years), and long-term (10+ years) actions based on both the urgency of adapting (how soon the department of transportation (DOT) needs to implement the strategy to protect against the projected climate changes) and the time period of implementation (how long it will take to implement the adaptation strategy based on planning, funding, and construction/programming time). The matrix of Climate Sensitive Decisions in Appendix A provides initial insight into the implementation time period by identifying the frequency with which the decisions are made. See the following table for examples of how the time period for implementation and the level of urgency could factor into strategy prioritization.

Table 7. Adaptation Strategy Prioritization, Implementation, Time and Urgency.

Adaptation Strategies	Time Period for Implementation	Level of Urgency	Prioritization
Strategy takes 0-5 years to implement, but does not need to be undertaken for another 30 years	Short	Low	Low
Strategy takes 0-5 years to implement, but should be undertaken now in order to be effective	Short	High	Medium
Strategy takes 30 years to implement, but should be undertaken now to ensure effectiveness	Long	High	High
Strategy should be undertaken in the near term because it will influence future decisions (e.g., long-term plans)	Ongoing	Medium	Medium

In addition, consider the existing repair and replacement cycle before implementing a stand-alone project. Proactive measures often make sense for high-value assets or assets that would be catastrophically damaged during extreme weather events, while continuous repair/maintenance (i.e., opportunistic adaptation efforts) is often the best approach for preparing for smaller, more frequent events and for assets that are less vulnerable to climate change.

4. Determine Improvements in Capabilities Necessary for Successful Implementation

Successful implementation of adaptation measures may require more overarching enhancements to the agency's capabilities. As described in Section II.E. FHWA has developed a primer that outlines six dimensions of capability that are closely associated with more effective TSMO activities (including those related to reducing climate change impacts).[27]

Improvements in one or more of these capabilities may be necessary to successfully implement the adaptation strategies discussed under "Identify Potential Adaptation Strategies." Table 8 denotes which of the above capabilities apply to a range of potential adaptation strategies.

27 FHWA Office of Operations, *Creating an Effective Program to Advance Transportation System Management and Operations: Primer,* FHWA-HOP-12-003 (Washington, DC, 2012). Available at: *http://ops.fhwa.dot.gov/Publications/fhwahop12003/background.htm*.

Table 8. Example Adaptation Strategies and Capability Maturity Framework Categories.

	Capability Maturity Framework Category						
Adaptation Strategies	**Business Processes**	**Systems & Technologies**	**Performance Management**	**Culture**	**Organization & Workforce**	**Collaboration**	**Maintenance**
Modify current design and procurement criteria to favor durable materials and designs (e.g., paints, paving materials, drainage features), factoring in likely future climate conditions.	X	X		X		X	X
Develop a system to track weather-related trends and costs over time (e.g., number of potholes repaired, snow removal costs, number of emergency event triggers, labor hours devoted to weather preparation, response, and recovery), such as through designated "weather-related" charge codes.	X	X	X				
Establish stand-by contracts for extreme event response.	X				X		
Provide a strategy for identifying trends in weather for budget setting, accounting for the fact that historical conditions are not necessarily representative of future conditions under a changing climate. - Consider weighting previous years differently. If higher cost years are weighted more heavily, they can provide a buffer in the budget. - In addition to a short-term average of previous year costs, consider looking at a longer trend line in costs and applying an incremental increase in the budget to account for the trend. - Consider adding a buffer in the budget forecast to account for the uncertainty in coming weather conditions.	X						
Consider the life-cycle costs of resiliency investments and savings in budgeting and design.	X						
Use asset management systems to track relevant information to inform decision making over time.	X						
Incorporate future Incorporate future transportation systems management and operations (TSMO) and maintenance needs into planning, design, and construction (e.g., require operations and maintenance signature approval on certain contracts and plans).	X			X		X	
Require after-action reports with clear recommendations for improvement following extreme events.	X						
Update emergency response plans to factor in potential for greater frequency of extreme weather events.	X						
Improve intra-agency coordination, information sharing about conditions, closures, resources, etc.				X		X	

Table 8. Example Adaptation Strategies and Capability Maturity Framework Categories (Continued).

Adaptation Strategies	Capability Maturity Framework Category: Business Processes	Systems & Technologies	Performance Management	Culture	Organization & Workforce	Collaboration	Maintenance
Improve inter-agency coordination, information sharing about plans, initiatives, risks, resources, etc. (e.g., include key stakeholders in routine communications to streamline process during emergency events).				X		X	
Harden emergency telecommunications systems.		X					
Invest in redundant communications systems.		X					
Invest in redundant data servers.		X					
Develop and track performance metrics related to extreme weather (e.g., number/duration of weather-related road closures).			X	X			
Purchase equipment, factoring in likely future needs based on extreme weather events or climate changes (e.g., versatile equipment in Alabama to double as snow plows, mobile stockpiles of traffic control devices).		X					X
Improve cross-training across staff (including across operations, maintenance, and emergency management).				X	X	X	X
Develop a system to track weather trends over time (e.g., Winter Severity Index, Summer Severity Index).	X		X				
Improve tracking of maintenance expenses and operational disruptions, including their cause and severity, and incorporate that information into budgeting processes over time.	X		X	X			
Stockpile materials (e.g., culvert pipe, temporary bridge components, fuel) and equipment (e.g., generators, chain saws, traffic control devices) and stage them in strategic areas prior to events.							X
Expand both coverage and quality of fixed and mobile monitoring capabilities within the agency.		X					
Increase coverage of real-time weather and roadway conditions using a combination of on-the-ground staff (and potentially citizens), sensors, and mobile technology.		X				X	
Establish honest and continued dialogue with the public about funding shortfalls, climate change, and prioritizations and realistic expectations of road clearance and level of service.				X			
Establish regular coordination between on-the-ground staff and other departments to discuss "hot spot" areas and inform investment decisions based on past performance.			X	X	X	X	X

Table 8. Example Adaptation Strategies and Capability Maturity Framework Categories (Continued).

Adaptation Strategies	Capability Maturity Framework Category: Business Processes	Systems & Technologies	Performance Management	Culture	Organization & Workforce	Collaboration	Maintenance
Leverage existing technologies such as Road Weather Information System (RWIS) to provide additional insight on climate change or respond to climate change. For example, portable RWIS could be deployed in areas that are particularly vulnerable to climate changes such as areas of flooding or extreme heat, and assist with tracking trends.		X					
Use Maintenance Decision Support Systems (MDSS) or other existing tools to run a series of hypothetical future storm events in order to inform operational planning exercises.		X					
Develop culture of information sharing, transition planning to ensure institutional knowledge is not vulnerable to retirement, workforce transitions, etc.				X			
Establish regular, structured discussion and collaboration between State departments of transportation (DOTs), the National Weather Service, State climatologists, US Geological Survey (USGS), and other relevant partners.				X		X	
Conduct table-top exercises or develop an approach for using "routine" emergencies to determine lines and communication and protocols (e.g., what to do when there is heavy snow blocking access to a hospital). Potentially include the public in practice drills (e.g., contraflow lanes).						X	
Review and consider mitigating vulnerabilities when conducting scheduled maintenance activities.							X

F. Monitor and Revisit

Monitoring and evaluating helps keep adaptation efforts on track as new information on climate risks emerges, evidence of the effectiveness of adaptation strategies becomes available, or other programmatic changes occur. Monitoring and evaluating serve to assess progress toward goals and objectives. These functions help an agency identify which activities are working well and which ones need to be refined.

The FHWA Framework describes the following steps as key to efforts to monitor and revisit: [28]

- Establish a monitoring and evaluation plan.
- Engage stakeholders.
- Monitor and collect data on relevant indicators.
- Evaluate the project and its outcomes.
- Revisit.

TSMO and maintenance programs are flexible (much more so than infrastructure planning and design decisions) and can evolve as conditions change.

28 FHWA Virtual Framework for Vulnerability Assessment, Available online at: *http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task6/page04.cfm*.

Monitoring trends in extreme weather events (such as frequency of particular events as well as impacts on TSMO and maintenance) and evaluating the effectiveness of actions will help to continually inform decision making. Monitoring trends in extreme weather events, for example, can help decision makers recognize when they need to manage for "new normal" conditions. As mentioned above, climate change refers to significant variations in temperature, precipitation, wind patterns, and other measures of climate lasting for an extended period of time. It may be decades before there is a robust enough set of data to attribute changes in trends to climate change. Such attribution is not necessary, though, to recognize that what once was rare is now routine.

Further, collection, storage, and analysis of monitoring weather data and the impacts of extreme weather events on TSMO, maintenance, and emergency managers (e.g., through post-event assessments and documentation) may be integrated into existing asset management systems or other systems to facilitate continuous or on-demand evaluation of the effectiveness of existing practices. This can also help to assess the need to revisit assumptions, underlying data, approaches, or program goals and objectives articulated at the outset.

Getting Started: Data Collection Best Practices

The more transportation agencies understand the effects of weather events on their system and how those events are changing over time, the better they can make decisions about how to plan for or otherwise manage these events.

Understanding changing weather effects requires collecting data and other metrics. Departments of transportation (DOTs) routinely collect and analyze large amounts of data on their operations and systems. As a result, the most effective way to collect additional information that will enable DOTs to learn about the effects of climate change will be to integrate data collection and analysis into existing processes. Potential existing processes that could serve as a "home" for weather and climate tracking include asset management programs, work order or labor tracking systems, weather severity indices, and performance measures.

Asset Management Programs

State DOTs are in the process of developing risk-based Transportation Asset Management Plans (TAMPs), in fulfillment of Moving Ahead for Progress in the 21st Century Act (MAP-21) requirements. TAMPs and associated asset management systems provide an opportunity for DOTs to integrate climate change risks alongside the other risks to transportation systems. Additional guidance is forthcoming from the National Cooperative Highway Research Program (NCHRP) on integrating climate change and extreme weather into TAMPs.[29] Below are some steps DOTs can take to capitalize on their asset management efforts to help inform their decision making around climate change.

- Incorporate fields into asset management system(s) to track the climate change or weather-related vulnerabilities of each asset, if known through a vulnerability assessment.
- Configure the system to provide alerts when vulnerable assets are due for maintenance, repair, or replacement.
- Incorporate fields to help monitor vulnerabilities and effectiveness of adaptation over time. Example fields may include:
    - Maintenance instances, including specific **cause** (flooding, extreme heat, extreme cold, etc. – more than just "weather-related") and **cost**.
    - Flooding frequency.
    - Work order frequency.

29 NCHRP 25-25/Task 94 (Active), "Integrating Climate Change and Extreme Weather Into Transportation Asset Management Plans," *http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3723*, accessed May 20, 2015.

Getting Started: Data Collection Best Practices (Continued)

- Incorporate fields that can help identify whether assets may be vulnerable. Example fields are listed based on relevant climate stressors:[30]
  - Temperature changes:
    - Pavement binder.
    - Material type/pavement type.
    - Joint type.
    - Annual average daily truck traffic.
  - Flooding:
    - Elevation.
    - Design standard (e.g., 25-yr, 50-yr, 100-yr).
    - For culverts: percent change in peak design flow required for overtopping.[31]
    - For bridges: approach elevation, span elevation, navigation vertical clearance.
    - Condition.
  - Any stressor:
    - Structure type.
    - Remaining useful life.
    - Age.
    - Usage (e.g., average annual daily traffic).
    - Detour length.
    - Historic status.
    - Criticality.
    - Whether the asset is component of a designated evacuation route.

Work Orders or Labor Tracking Systems

DOTs typically have systems in place to track employee activities and expenses, at least to an extent. DOTs can leverage these systems to better track the impacts of weather events over time by creating work order numbers, charge codes, or similar codes tied specifically to weather events.

- Set up work order codes for:
  - Individual weather events (specific storms), or
  - Categories of weather events (heat, snow/ice, rain, storm).
- Instruct staff to charge their time and expenses to the appropriate work order code. This will allow tracking of agency costs including:
  - Labor costs – regular and overtime.
  - Contractor costs.
  - Materials costs.
  - Equipment costs.
- Associate societal impacts the agency is already monitoring with specific weather events or event types. These impacts may include:
  - Delays.
  - Accidents.
  - Fatalities.

30 U.S. Department of Transportation, "Transportation Climate Change Sensitivity Matrix." Available at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules/index.cfm?moduleid=2, accessed May 20, 2015.

31 MnDOT, MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project, Final report prepared for the Minnesota DOT and the USDOT FHWA by Parsons Brinckerhoff and Catalysis Adaptation Partners, 2014.

Getting Started: Data Collection Best Practices (Continued)

Using Work Order Numbers to Track Weather Event Costs

The Southeastern Pennsylvania Transportation Authority (SEPTA) began creating unique work order numbers for weather events in 2012, beginning with Hurricane Sandy.

SEPTA created a unique work order number in advance of the storm and instructed staff to use that number for any time or materials spent on storm preparation, response, and recovery.

As a result, SEPTA captured a much fuller picture of the impacts of Sandy on their operations than they had for previous storms. For example, SEPTA recorded more than $1.3 million in labor costs, nearly ten times the labor costs recorded during previous tropical storms—storms that were much more destructive to SEPTA than Sandy.

Reference: ICF International, 2013, A Vulnerability and Risk Assessment of SEPTA's Regional Rail: A Transit Climate Change Adaptation Assessment Pilot, Federal Transit Administration (FTA Report No. 0071). Available at: *http://www.fta.dot.gov/documents/FTA_Report_No._0071.pdf*, accessed May 20, 2015.

Weather Severity Indices

Many DOTs (including Wisconsin, Indiana, Iowa, Idaho, Minnesota, and Ontario) maintain a "Winter Severity Index" or similar metric that allows them to compare their seasonal expenditures to the relative severity of winter weather.[32] DOTs use these indices to identify efficiencies in winter weather response over time and inform budget forecasts.

DOTs may consider tracking similar severity indices for other types of weather events that affect their operations. For example:

- Summer severity index – This may include calculation of degree-days above a certain temperature threshold, similar to how the energy sector tracks cooling degree-days.
- Flooding severity index.
- Wildfire season severity index.
- Storm season severity index – tracking the frequency and severity of convective thunderstorm or other storms on a more seasonal basis.
- Drought severity index (these already exist in other sectors – such as the Palmer Drought Severity Index – and would be available from the United States Drought Monitor or other agencies within the State).

32 Will Farr and Leigh Sturges, 2012, Utah Winter Severity Index Phase 1, Utah Department of Transportation. Available at: *http://www.udot.utah.gov/main/uconowner.gf?n=11539601019505676*, accessed May 20, 2015.

Getting Started: Data Collection Best Practices (Continued)

In addition, DOTs may consider identifying specific impacts associated with climate changes and tracking the frequency of these impacts over time. This could provide a way to simplify the data tracking process by focusing on one or two key metrics of vulnerabilities over time, such as those in Table 9.

Table 9. Example Metrics to Track Impacts of Climate Stressors over Time.

Climate Stressor	Impact Metrics
Extreme Heat	Pavement rutting/shoving Concrete joint heaving
Flooding (rain-driven or coastal)	Road closures associated with flooding (frequency, duration) Washouts associated with flooding
Wind	Road closures associated with high winds
Drought	Pavement cracks
Changes in Freeze/Thaw	Potholes
Permafrost Thaw	Timing of permafrost thaw

Performance Measures

Finally, linking agency performance measures that are already tracked and analyzed to weather, where appropriate, can be a good way to "mainstream" weather impact data collection. See Section III.E.I for additional information on linking performance measures to climate change.

Potential Pitfalls of Data Collection

Potential (but avoidable) pitfalls to implementing any of these data collection strategies do exist. Departments of transportation (DOTs) should note these possible drawbacks early and take steps to avoid them.

- **Data Storage -** DOTs need the Information technology (IT) infrastructure to house what could become potentially large datasets over time. Coordinate with the IT department to ensure the data collection plan is sustainable from their perspective.
- **Staff Time -** Data cannot inform decision making without first being analyzed. Analysis of these data sources needs to be expressly integrated into someone's job in order for that analysis to happen. The purpose of the approaches outlined above is to identify opportunities to integrate climate and weather impact tracking data into existing data collection and analysis efforts to minimize the risk that data go unused.

IV. Getting Started

This guide provides information and resources to help Department of transportation (DOT) transportation systems management and operations (TSMO) and maintenance staff use TSMO, maintenance, and emergency management activities to increase the resilience of their agency to extreme weather events and climate change. The materials presented throughout this guide will help State DOTs and other transportation agencies to better understand the risks that climate change poses and actions that can help reduce those risks.

There is already sufficient information to begin a more concerted effort to evaluate programs and begin to make or plan to make adjustments today. New information will also continue to emerge regarding anticipated risks and strategies to address those risks. As it does and as the framework and concepts presented in this guide are put into practice, it will be important to revisit and refine this guidance.

In the meantime, the specific resources and checklists provided throughout Section IV of this guide in the "Getting Started" text boxes will enable users to use the segments of the guide best suited to their individual needs, level of familiarity with climate change adaptation, and readiness to get started on planning and implementing adaptation measures.

Appendix A. Matrix of Climate-Sensitive Decisions

The following table lists the potential decisions that are often encountered by transportation systems management and operations (TSMO) and maintenance groups that are sensitive to changes in climate and extreme weather. Generated by the research team using their knowledge of State and local department of transportation (DOT) practices, these decisions will provide the basis for developing adaptation strategies that mitigate the risk associated with the decision due to climate change.

Table 10. Climate-Sensitive Decisions.

						Sensitivity to Climage Change Stressors												
Climate-Sensitive Decision Areas	**Specific Decisions**	**Description**	**Description of How Climate Stressors Affect This Decision (i.e., Climate Sensitivity of Decision)**	**Decision Time Frame**	**Single Decision Point?**	**Increase in Average Temperature**	**Increase in Annual Precipitation**	**Sea Level Rise**	**Change in Freeze/Thaw Cycles**	**Changing Snowpack**	**Extreme Temps (Heat)**	**Extreme Temps (Cold)**	**Extreme Precipitation (Amount/Intensity)**	**Storm Surge**	**Wildfires**	**Dust Storms**	**Wind**	**Ecological Effects**
1. Planning for future workforce needs	Determine the right level of workforce requirements and capabilities	Operating and emergency management agencies make a variety of workforce-related decisions, including the number of staff required, their locations, and the abilities necessary to monitor, control, report, and maintain the roadway system.	Increased frequency of extreme events requires additional personnel to monitor, control, report, and respond to events. Changes in long-term climate trends may also change seasonal work requirements (e.g., changes in winter weather seasons, construction timing, or landscaping timing) and additional or unique staff expertise to monitor and respond to new types of climate events (e.g., snow storm in Atlanta).	Long-term	No	X	X	X	X	X	X	X	X	X	X	X	X	X
2. Planning for operations and maintenance investments	Determine criteria to prioritize operational resource investments (including capital improvements)	Resource investments may include new capital improvements for operations and maintenance such as control systems, field equipment, vehicles, communications, and power. They may also include investments for annual maintenance.	Capital improvements should be designed to withstand the climate changes anticipated over their useful life. For this reason, all climate stressors should be considered to ensure investments will make it to the end of their useful life. Whether features of a project reduce its climate risk or reduce the climate risk of the community (e.g., reduce flooding) would need to be factored into decisions around which investments to make. Additionally, capital investment needs may be changing and therefore may require new identification processes (e.g., increased flood monitors).	Long-term		X	X	X	X	X	X	X	X	X	X	X	X	X
3. Budgeting for operations, maintenance, and emergency management	Determine the appropriate funding needs and levels on annual and multi-year basis	Operating and emergency management agencies are typically funded on an annual basis. Funding levels are a driving factor in overall program capabilities and functions.	Extreme events and long-term changes in climate can affect resource requirements. For example, increases in temperature can increase annual pavement maintenance costs, or changes in freeze/thaw cycles can increase potholes. Changes in winter weather and increasing weather uncertainty could also affect budgets. The future climate may require different resource allocations and budget planning formulas than today's climate.	Annual	Yes	X	X		X	X	X	X	X	X	X	X	X	X
4. Establishing realistic objectives	Set regional operational and emergency management objectives for the program	Effective planning for operations and emergency management requires a clear articulation of regional operating objectives. These objectives define the response strategies and the performance-based management required.	Objectives and performance measures relating to emergency response or return to level of service may be affected by the frequency and severity of extreme events. Additional measures on resilience might be required to monitor and manage performance. Additionally, changes in weather patterns may make select past performance measures unrealistic. The setting of realistic targets will need to be grounded in an understanding of future weather conditions.	Annual	Yes	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 10. Climate-Sensitive Decisions (Continued).

Climate-Sensitive Decision Areas	Specific Decisions	Description	Description of How Climate Stressors Affect This Decision (i.e., Climate Sensitivity of Decision)	Decision Time Frame	Single Decision Point?	Sensitivity to Climage Change Stressors												
						Increase in Average Temperature	Increase in Annual Precipitation	Sea Level Rise	Change in Freeze/Thaw Cycles	Changing Snowpack	Extreme Temps (Heat)	Extreme Temps (Cold)	Extreme Precipitation (Amount/Intensity)	Storm Surge	Wildfires	Dust Storms	Wind	Ecological Effects
5. Assessing future technology and system requirements	Determine the type of monitoring equipment and sources, communication needs, siting criteria and suitability to conditions	Monitoring field conditions is vital to effective operations and emergency management. The type of monitoring equipment and the available sources of data greatly determine the capability to respond. Sensitive to cost, these decisions provide the required situational awareness to agencies.	Monitoring equipment (e.g., cameras, loop detectors) is sensitive to weather extremes and flooding. They can over heat, freeze, or be corroded by water infiltration. Climate change may also require agencies to monitor additional stressors/conditions in order to understand how they may affect the agency in the future. Early monitoring of climate change stressors could improve agency abilities to make decisions in the long-term.	Near-term/ Mid-term/ Long-term	Yes	X	X	X	X	X	X	X	X	X	X	X	X	X
		Closely related to the type of equipment is the correct "siting" of the equipment to ensure the right extent of coverage on the system. While some pressure of the decision is alleviated through newly available sources of data such as probes and private sector data, other monitoring systems such as Environmental Sensing Stations are greatly affected by the siting criteria.	Siting equipment in areas that will be impacted by sea level rise, ecological damage, flooding, snowfall, or other climatic events may damage the infrastructure. Climate change could also affect where agencies choose to site new equipment. Flood risk over the lifetime of the asset could be a criteria used to choose sites for future equipment. Additionally, agencies cannot afford to monitor all areas and assets that will be impacted by climate change. Prioritization methods and flexible mobile data sources (e.g., citizen reporters, snow patrol reporting, mobile probes) will need to be developed.	Long-term	Yes			X		X	X	X	X	X	X	X	X	X
		Establishing adequate communications and power, especially redundancy in the system, is critical to prevent outages of the field and control systems. The susceptibility of communications and power infrastructure to conditions can limit the capability of operational response.	Communication and power lines are sensitive to icing, flooding, and extreme temperatures (e.g., rolling blackouts during heat waves). Flooding can also damage back-up power systems. Storms can bring down tree lines which damage power and communication lines. Agencies will need to consider whether their existing communication and power requirements are resilient to climate change. Snow can cover or block communications (e.g., stop lights and cameras).	Long-term	No					X	X	X	X	X	X		X	

Table 10. Climate-Sensitive Decisions (Continued).

Climate-Sensitive Decision Areas	Specific Decisions	Description	Description of How Climate Stressors Affect This Decision (i.e., Climate Sensitivity of Decision)	Decision Time Frame	Single Decision Point?	Sensitivity to Climage Change Stressors												
						Increase in Average Temperature	Increase in Annual Precipitation	Sea Level Rise	Change in Freeze/Thaw Cycles	Changing Snowpack	Extreme Temps (Heat)	Extreme Temps (Cold)	Extreme Precipitation (Amount/Intensity)	Storm Surge	Wildfires	Dust Storms	Wind	Ecological Effects
6. Determining future maintenance needs	Determine the required level and precision of inspection protocols	Inspection protocols are a vital part of asset management. For operating agencies, these include the full range of transportation assets from structures to communication networks. Due to resource constraints, agencies need to develop a protocol designed to prioritize the key assets being managed.	Climate stressors can lead to increased asset deterioration, requiring more frequent inspections. However, inspections are very expensive and time consuming. Knowledge of climatic trends may allow for focused scoping of the level of precision and frequency of various types of inspections.	Long-term	No	X	X	X	X	X	X	X	X	X	X	X	X	X
	Determine pavement rehabilitation needs and methods	A variety of pavement rehabilitation decisions are made on a seasonal basis ranging from full-depth replacement, to levelling and coating. Decisions pertaining to life-cycle cost of such treatments, the timing of these treatments, and the materials used are all topics of concern to decision makers.	Pavements are designed to withstand particular temperature thresholds. High temperatures may lead to rutting, while cold (and freezing) conditions increase potholes. This may necessitate changing the pavement mix or rehabbing roads earlier.	Long-term	Yes	X	X	X	X	X	X	X	X		X			X
	Determine bridge maintenance needs and methods	Bridges are natural chokepoints and potential points of failure. Agencies justifiably invest in bridge management programs involving preventative maintenance and rehabilitation.	Bridges with joints and moveable parts are more susceptible to damage due to their sensitivity to temperature and water infiltration. Increased rainfall and flooding can also increase bridge scour or lead to washouts and debris deposits. Changes in climate may necessitate earlier or different maintenance approaches.	Long-term	Yes: Maintenance No: Monitoring			X	X	X	X	X	X	X	X		X	X

Table 10. Climate-Sensitive Decisions (Continued).

Climate-Sensitive Decision Areas	Specific Decisions	Description	Description of How Climate Stressors Affect This Decision (i.e., Climate Sensitivity of Decision)	Decision Time Frame	Single Decision Point?	Sensitivity to Climage Change Stressors												
						Increase in Average Temperature	Increase in Annual Precipitation	Sea Level Rise	Change in Freeze/Thaw Cycles	Changing Snowpack	Extreme Temps (Heat)	Extreme Temps (Cold)	Extreme Precipitation (Amount/Intensity)	Storm Surge	Wildfires	Dust Storms	Wind	Ecological Effects
7. Modifying maintenance practices and approaches	Determine construction and maintenance work timelines and timeframes	Construction and maintenance work is usually conducted under very specific weather conditions. The number and length of these windows of opportunity to conduct work may be shortened or lengthened depending on regional climate trends. This would also impact construction contracts and crew contracts.	Increased frequency of precipitation (especially extreme precipitation), and increased high heat days may decrease worker safety and result in delays in construction. Decreases in these events could accelerate construction periods. Certain elements of construction (e.g., laying concrete, painting roads) can only be accomplished during a narrow range of weather conditions. Changes in weather will impact the length of the construction season and the contracts with construction companies.	Mid-range	No	X			X		X	X	X		X	X	X	
	Develop approach for overall right-of-way maintenance including vegetation control	Decisions involving overall right-of-way maintenance such as vegetation control, drainage, and culvert management are included in this area. Often deferred due to resource constraints, effective decisions in this area may in fact be more critical to operational capability than anticipated.	Vegetation control: Increased rain (in some parts of the country) paired with increased temperatures can lead to additional vegetation growth and death. This dry fuel poses wildfire hazards. Some areas may begin to experience drought and need to plant more drought-tolerant vegetation. Drainage and culverts: Following wildfires, rainstorms can increase debris flow and block or flood culverts and drainage systems. Heavy rainstorms can blow out undersized drainage. In coastal settings, sea level rise may surcharge the drainage systems.	Annual	No	X	X		X	X	X	X	X	X	X	X	X	X
	Determine the amount, cost, timing of material procurement	Agencies spent a significant portion of their budget on materials. Procurement decisions ranging from timing, type of material, and the length of the contract duration greatly affect the overall cost as well as the actual season.	If supplies are under-purchased during particularly bad seasons, it may be difficult to obtain the necessary materials for response. Frequently, after an extreme weather event (e.g., ice storm or hurricane), supplies can run short and distribution lines can be disrupted. Likewise, if response contracts are too short then agencies may not be prepared to respond to late season extreme weather events (e.g., flooding, extreme heat, snow).	Seasonal	Yes				X	X	X	X	X	X	X			
8. Protecting facilities and assets	Develop criteria for determining facility locations and asset protection strategy	Decisions and techniques for reducing flood damage to essential utility systems and equipment.	When siting new facilities, agencies should consider the impacts of climate change on the location (e.g., sea level rise, flooding).	Long-term	Yes		X	X	X	X			X	X	X		X	X

Table 10. Climate-Sensitive Decisions (Continued).

Climate-Sensitive Decision Areas	Specific Decisions	Description	Description of How Climate Stressors Affect This Decision (i.e., Climate Sensitivity of Decision)	Decision Time Frame	Single Decision Point?	Sensitivity to Climage Change Stressors												
						Increase in Average Temperature	Increase in Annual Precipitation	Sea Level Rise	Change in Freeze/Thaw Cycles	Changing Snowpack	Extreme Temps (Heat)	Extreme Temps (Cold)	Extreme Precipitation (Amount/Intensity)	Storm Surge	Wildfires	Dust Storms	Wind	Ecological Effects
9. Maintaining mobility and safety	Plan for maintenance of traffic	Maintenance of traffic involves developing an approach to maintain and restore mobility and accessibility in a region. These may involve posted detours, communications, lane management, etc.	Flooding or other extreme weather may cause long-term disruptions to traffic. A plan for maintenance of traffic needs to be developed. In some cases, this may require significant detours and wide area communications to support adequate traveler information.	Seasonal	No			X		X			X	X	X	X	X	X
	Determine the mix of operational strategies to deal with surge demand	Operating agencies are geared towards dealing with reliability issues and generally have a good idea of demand-supply relationships on their systems. In cases of emergencies and adverse weather, the shift from reliability to resiliency is required to manage surges in demand. This requires revisiting the approach to implement the operational strategies.	Changes in the frequency of short-term weather events influence traffic demand (e.g., rainfall events, additional driving on high heat days) and thus require varied operational responses.	Immediate	No					X	X	X	X	X	X	X	X	

Appendix B. Additional Resources

Many resources are provided throughout this document. This appendix provides a few additional resources that may be of interest and use to agencies seeking to embark on adaptation planning.

A. Federal Highway Administration Virtual Framework

The Federal Highway Administration (FHWA) "Virtual Framework for Vulnerability Assessment" (Virtual Framework) is an interactive web version of FHWA's 2012 Climate Change and Extreme Weather Vulnerability Assessment Framework. The Virtual Framework provides guidance to State departments of transportation (DOTs) and other transportation agencies on how to assess and address their vulnerabilities to climate change. The Virtual Framework breaks the vulnerability assessment process into six modules: Articulate Objectives, Identify Key Climate Variables, Characterize and Select Assets, Assess Vulnerabilities, Integrate Vulnerabilities into Decision Making, and Monitor and Revisit.

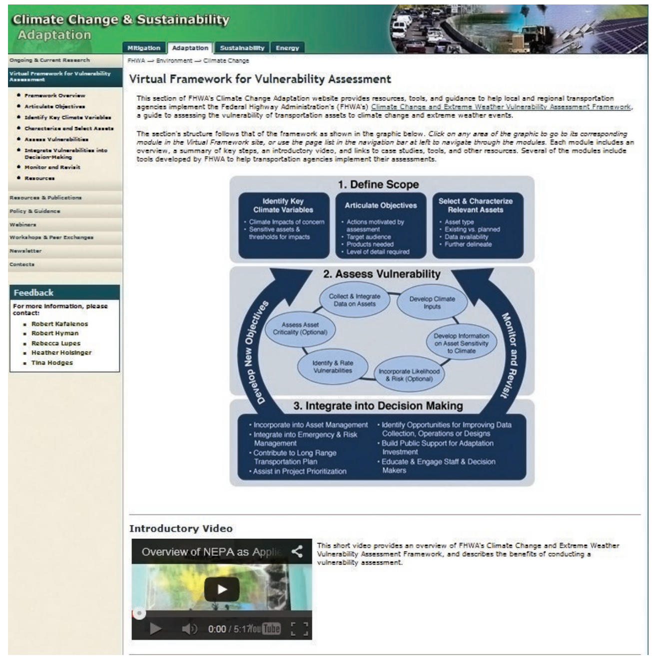

Figure 13. Screenshot. FHWA Virtual Framework for Vulnerability Assessment.

Each module contains step-by-step guidance, video testimonials from professionals sharing lessons on their experience, case studies related to the framework step, links to resources related to the step, and tools to help a user complete the step. The Virtual Framework is primarily focused on assessing and addressing infrastructure-related vulnerabilities, but offers several resources that can prove useful to adapting TSMO and maintenance practices. This guide identifies specific resources within the Virtual Framework as they apply to the steps outlined herein. Readers are encouraged to explore the Virtual Framework for additional resources that may be relevant to their organization. The Virtual Framework is available at: *http://www.fhwa.dot.gov/environment/adaptationframework*.

B. Existing Benefit-Cost Assessment Tools

A number of guidance documents and tools for conducting cost benefit assessments are available for the transportation sector. Some guidance documents, like United States Department of Transportation's (USDOT's) Asset Management Primer or Operations Benefit/cost Analysis Desk Reference, are intended to inform a particular type of decision or decision maker, but do not address adaptation and extreme events directly. Some, like National Cooperative Highway Research Program (NCHRP) Report 750, Climate Change, Extreme Weather Events, and the Highway System, provide a high-level discussion of climate-risk-adjusted benefit-cost-methodology, but do not provide a comprehensive set of resources or guidance for each step of the analysis. The various tools that exist—such as BCA.net or the Hazard Mitigation Cost Effectiveness (HMCE) tool—also vary in their audiences, in the types of inputs and outputs they produce, in the scalability of the projects they can evaluate, and in their ability to capture extreme events or climate change. A sampling of existing tools and resources is shown in the box below.

Sample of Existing Tools and Resources

- *National Cooperative Highway Research Program (NCHRP) 750 Vol. 2* - Benefit Cost Methodology for Climate Adaptation Strategies.
- *Federal Transit Administration (FTA) Hazard Mitigation Cost Effectiveness (HMCE) Tool* - used to assess the cost-effectiveness of transit resilience projects.
- *Federal Highway Administration (FHWA) Operations/Cost Analysis Desk Reference* - an overview of analysis tools.
- Coastal Adaptation to Sea Level Rise (COAST) tool - calculates cumulative damages from multiple storms.
- *FHWA Economic Analysis Primer* - principles, concepts, and methods for performing economic analyses.
- *Transportation Research Board (TRB) Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System* - quantifying indirect costs.
- *Hazus* - estimate potential losses from earthquakes, floods and hurricanes.
- *Beach-fx* - evaluate benefits and costs of shore protection projects.
- *United States Department of Transportation's (USDOT) Transportation Investment Generating Economic Recovery (TIGER) - Benefit-Cost Analysis (BCA) Guidance*.
- *Federal Emergency Management Agency (FEMA) Benefit Cost Toolkit* - required when applying to the Hazard Mitigation Grant Program.
- *Irregular Operations (IROPS) Investment Support (IRIS) Decision Support Tool* - multi-criteria decision tool for mitigating airport irregular operations.
- *From Risk to Resilience by International Institute for Applied Systems Analysis (IIASA)* - cost-benefit analysis approach for disaster risk management.
- *USDOT Guidance on the Value of Time* - values for time during delay and time savings.
- *BCA.net* - step-by-step approach to conducting benefit cost analyses (BCAs).
- *USDOT Guidance on Treatment of the Economic Value of a Statistical Life*.
- *Economic Commission for Latin American and the Carribean (ECLAC) Handbook on socioeconomics of extreme events*.
- *Belize Climate Resilient Infrastructure Program* - simplified BCA screening tool for data poor regions.
- *FHWA Climate Resiliency Pilots and Hurricane Sandy Resilience Project* - approaches to conducting BCAs.
- *United Kingdom (UK) Climate Impacts Programme: Costing the Impacts of Climate Change in the United Kingdom*.

C. International Efforts

The Hellenic Institute of Transport published a review of transportation adaptation strategies in 2015.[33] Example adaptation strategies related to transportation systems management and operations (TSMO) and maintenance are listed in the text box below.

Example Adaptation Strategies Related to transportation systems management and operations (TSMO) and Maintenance from Hellenic Institute of Transport's Roadmaps for Adaptation Measures Project

Procedural and operational options

- Organization of the supply of trapped drivers/passengers with the help of volunteers and aid organizations.
- Adaptation of timetables and service intensities under adverse weather conditions.
- Need for alternate routes for freight transport in Arctic areas.

33 Stamos, E. Mitsakis, and J.M. Salanova Grau, *"Roadmaps for adaptation measures of transportation to climate change,"* Transportation Research Record (Washington, DC: 2015). Available at: http://trid.trb.org/view.aspx?id=1338251.

Example Adaptation Strategies Related to transportation systems management and operations (TSMO) and Maintenance from Hellenic Institute of Transport's Roadmaps for Adaptation Measures Project (Continued)

- Priority plans that maintain access to hospitals, emergency stations.
- Definition of priority routes for road clearance in case of large scale impacts.
- Tracking of "chain reactions" of extreme weather events, particularly in agglomeration areas.
- Coordination of emergency plans amongst transport modes and networks.
- Implementation of appropriate risk management procedures in order to be prepared for adverse conditions.

Organizational and decision making processes

- Setting and implementation of international standards for weather and emergency information.
- Consultation with and coordination of highway authorities, subcontractors, suppliers, and key stakeholders to adjust adaptation strategies.
- Establishment of networks of urban, regional, and national stakeholders: transport companies, authorities, and users.
- Issuance of educational and information material on emergency cases, planning and maintenance to related authorities.
- Public campaigns to raise public awareness regarding local hazards.

Technical options

- Provision of shelters for non-motorized transportation.
- Preparation for sufficient salt stocks and road clearing equipment availability before and during winter or storm seasons.
- Development of timely communication and coordination plans involving stakeholders and freight operator associations.
- Roadside vegetation, absorbing generated heat, protecting roads.
- Enhancement of road layers to prevent washing-off.
- Measures of protection against slope subsidence around road/rail network to avoid cut off links.
- Additional pumping in tunnels.
- Installation of wind-breakers.
- Regular clearance of cycle lanes and sidewalks during winter.

Information flow and information and communications technology support

- Development of sustainable business models for the provision of emergency information systems.
- Provision of reliable, instant, and, if feasible, personalized information on duration of the incident and travel options.
- Installation of signs that warn the driver/pedestrian on upcoming flooded network.
- Development of intelligent feedback systems in vehicles to sustain user attention.
- Adoption of operational, physical, technical, procedural, and institutional integration of weather and traffic control services.
- Preparation of broad communication on disruptions and alternatives with the public, using a variety of communication channels.

Legislative options

- Strict speed limit enforcement during storms.
- Review of maintenance contracts and procedures to make them flexible and effective even under rapidly changing weather conditions.

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Appendix C. Future Research Needs

This guide begins to lay out how climate change will impact transportation systems management and operations (TSMO) and maintenance and provides actionable steps that practitioners can take to prepare their programs; however, there are still many topics that require additional research and development. In order to identify the remaining gaps in knowledge, the following table presents existing needs in TSMO and maintenance capabilities to address climate change, the actions that need to be undertaken to move toward a climate resilient program, and the research that remains to be completed to allow departments of transportation (DOTs) to take informed actions to close the gaps.

Table 11. Inventory of Gaps in TSMO and Maintenance Capabilities to Address Climate Change and Future Research Needs.

Gap Category	Gap	Actions Toward a Climate-Resilient Program	Future Research Needs
Business Processes	Departments of transportation (DOTs) often do not track the costs of maintenance or damage related to weather events, which limits their ability to understand changing costs over time (e.g., related to repeated repairs due to recurring impacts).	Track the reason for damage and the cost of repair, and incorporate that information (e.g., Winter Severity Indices) into budgeting processes.	Guide for integrating data tracking into asset management systems and their routine procedures.
	DOTs rely on historic weather data in their decision making. They do not have sufficient long-range (1-3 months or 1-3 years) meteorological forecasts to use in their budget setting process. They face both a lack of data in addition to a lack of understanding of how to use uncertain climate projections in decision making.	Consider potential future climatic conditions (and associated uncertainty) when setting TSMO and maintenance budgets and workforce planning.	• Enhanced metrological forecasts that account for local weather variations (e.g., El Niño's) and global climate change. Projections in the 1-3 year time frame would be helpful in informing budget setting processes. • Develop decision support tools that better incorporate probabilistic information (i.e., a computer-based approach). • Develop training materials on how to interpret probabilistic information (i.e., a human-based approach).
	DOT weather maintenance budgets are frequently insufficient to allow for the advanced preparation for extreme events such as investing in equipment, investing in labor, and stockpiling materials and supplies (e.g., culverts) prior to a damaging event; however, after extreme events, supply chains are frequently disrupted, materials may be in short supply, and the rushed nature of ordering after an emergency can increase costs. This results in delays in repairing and reopening roadways.	Have sufficient resources to prepare in advance for the coming season in terms of labor, equipment, and materials. Stockpile extreme weather response materials and supplies in advance of extreme events. Redistribute materials prior to an extreme weather event to ensure efficient access to needed supplies.	Methods for quantifying the benefit of increased preparedness and the costs associated with delayed repairs.
	DOT personnel are constrained in their ability to justify increases in current budgets, despite potential savings over time. They have limited information and tools to determine the long-term cost effectiveness of actively investing in resiliency during routine maintenance versus responding after issues arise.	Consider the life-cycle cost effectiveness of resiliency investments in budgeting and design. Use asset management systems to track relevant information to inform decision-making over time.	Methods for quantifying the benefit of increased preparedness and the costs associated with delayed repairs.

Table 11. Inventory of Gaps in TSMO and Maintenance Capabilities to Address Climate Change and Future Research Needs (Continued).

Gap Category	Gap	Actions Toward a Climate-Resilient Program	Future Research Needs
Business Processes	DOT TSMO programs traditionally focus on improving daily operations (e.g., managing recurrent delay) rather than proactively developing systems and protocols for managing extreme weather events. They are unaware of how adapting TSMO and maintenance to climate change differs from (and is linked to) routine preparation for extreme weather events.	Link climate change considerations to asset management systems and use a strategic approach to prioritize investments between improving operations on the average day and improving operations during extreme weather events. Additionally, prioritize investments and changes in practices that benefit both the near and short term.	A framework for prioritizing investments that includes short-term and long-term needs.
Systems and Technology	Many DOTs have significant gaps in coverage of weather and road weather conditions. This makes it difficult to make informed decisions during extreme weather events.	Use a combination of on-the-ground staff (and potentially citizens), sensors, and mobile technology to gain comprehensive coverage of real-time weather and roadway conditions.	Viability of conducting real-time data mining from social media websites to inform immediate operations responses and longer-term planning.
	Many DOTs optimize their signal timing and other TSMO tools for managing recurrent delay rather than managing extreme weather events. While this approach is effective for increasing reliability, it might not be the best approach for using these tools to increase resiliency to weather events.	Take full advantage of TSMO technologies both during daily recurrent traffic conditions as well as during extreme weather events.	Additional research on the adaptability of specific technologies and systems.
	DOTs need a projection period of more than a few days to fully prepare a response to a weather event. Existing tools (e.g., theMaintenance Decision Support System [MDSS] program) are available only for winter weather and currently only project weather conditions 2 to 3 days out (and have limited geographic scope).	Use MDSS or other existing tools to run a series of hypothetical future storm events in order to inform operational planning exercises. Use detailed road weather projections to project further out in order to inform an event-specific staging and response.	Enhancements and geographic expansion of the MDSS program.
	Practitioners other than winter maintenance managers do not have decision support systems in place to manage the system based on near-term or longer-term weather.	Develop MDSS systems that cover weather events such has floods and heat waves.	Enhancements and geographic expansion of the MDSS program.

Table 11. Inventory of Gaps in TSMO and Maintenance Capabilities to Address Climate Change and Future Research Needs (Continued).

Gap Category	Gap	Actions Toward a Climate-Resilient Program	Future Research Needs
Systems and Technology (continued)	DOTs are unaware of how they could adapt their practices and technology to respond to climate change.	Review a wide range of potential adaptation options and best practices in order to identify priority actions, especially those that may offer co-benefits.	DOTs need a database of potential adaptation activities and best practices for consideration to help understand the range of options. While we can begin to provide these list of options, future research will need to develop implementation time frames, partners, co-benefits, and cost of implementation assessments.
Performance Measurement	Existing definitions of risk tolerance and the acceptable level of operational performance do not account for the potential impacts of climate change. It may become more difficult to meet existing performance measures and targets with a changing climate.	Revisit performance measures on a regular basis and, in light of climate change and budgets, revise the measures to accurately reflect achievable levels of service. Risk tolerance levels and performance standards would take into account changes in climate and the potential impact on their ability to maintain historical levels of service.	Develop a framework for assessing how climate change may impact agencies ability to manage the projected risks posed by severe weather within established levels of risk tolerance (i.e., when will traditional tactics used for routine events be insufficient?). Include how to assess the agency's current capability to handle threats.
Culture	TSMO, maintenance, and emergency management staff is unaware of how climate change may impact their operations, both in the near term and the future. There is also inconsistent agreement among State DOTs that climate change is a real threat that needs to be integrated into decision making.	Understand climate sensitive decisions, the impacts of climate change (both primary and secondary/cascading impacts), and the need to proactively respond to this threat would be present throughout the organization.	Continued research on the impacts of climate change on specific elements of TSMO programs. Further documentation of climate-sensitive TSMO and maintenance decisions.
	DOTs have difficulty managing expectations from the public for ever-clear roads, which is in direct conflict with decreasing State funding and more frequent extreme weather events.	Engage in honest and continued dialogue with the public about funding shortfalls, climate change, and prioritizations as well as realistic expectations for road clearance and level of service.	Best practices on community engagement and discussion.
	DOTs are historically risk averse and do not want to change practices until they are required to (as a result of breakdowns in the existing system).	Consider climate change impacts throughout TSMO and maintenance practices in order to minimize risk and vulnerability to weather events.	Continue to identify barriers to and best practices for changing DOT culture to accept the need for climate resilience.

Table 11. Inventory of Gaps in TSMO and Maintenance Capabilities to Address Climate Change and Future Research Needs (Continued).

Gap Category	Gap	Actions Toward a Climate-Resilient Program	Future Research Needs
Organization and Workforce	Information is not always full reported as to where problems repeatedly arise and why. This lack of information sharing limits the ability of TSMO, maintenance, and emergency management staff to optimize their response to climate change.	Share data and qualitative lessons learned on frequent problem areas and proposed actions to mitigate these issues.	Potential citizen reporting technology development for tracking persistent issues (e.g., nuisance flooding).
	DOT staff currently report that they are overburdened by current job responsibilities and have limited to no capacity or training to take on additional responsibilities, such as climate change risk and vulnerability assessments and developing adaptation responses.	Ensure all TSMO, maintenance, and emergency management staff understands how climate change and extreme weather affect their day-to-day ability to efficiently complete their jobs. With this understanding should come internal initiative to increase resiliency to these events.	Outline of approaches to mainstreaming climate change into TSMO and maintenance practices.
	DOT staff does not necessarily have the skill sets necessary to incorporate climate change into day-to-day operations.	Add new job classifications to the workforce, such as meteorologists, hybrid engineer/environmentalist, people from other hybrid disciplines, TSMO managers, risk experts, emergency managers with both a transportation/emergency management background, etc.	Steps needed to develop a workforce that can address external factors – whether climate change or something else that affects the operational component. With a range of skill sets needed, how to build and maintain a team of diverse capabilities. Develop wiring diagrams to show the connected responsibilities among offices.
	In addition to not tracking the quantitative costs of responding to extreme weather events, most DOTs also do not record qualitative information that comes from years of professional staff experience. This makes it hard to retain historic, qualitative information when staff retire or move on.	Regularly coordinate between on-the-ground staff and other departments to discuss "hot spot" areas and inform investment decisions based on past performance.	Guidebook on succession planning.

Table 11. Inventory of Gaps in TSMO and Maintenance Capabilities to Address Climate Change and Future Research Needs (Continued).

Gap Category	Gap	Actions Toward a Climate-Resilient Program	Future Research Needs
Collaboration	Most DOTs do not coordinate emergency response plans with private companies, resulting in increased public frustration and lack of essential supplies during extreme weather events (which may become a more frequent concern under a changing climate and, thus, a more frequent issue).	Coordinate emergency plans with banks, gasoline providers, inter-regional motor coach carriers (e.g. Greyhound, Peter Pan), and other private sector companies to ensure access to critical needs during and following a severe weather event.	Develop best practices for public/private coordination on emergency plans.
	DOTs are not used to or comfortable collaborating with climate scientists to obtain information on climate change projections and discussing and determining how to integrate this data and the inherent uncertainty into planning and practices.	Collaborate with climate scientists to understand the types of uncertainty in climate change modeling and the range of uncertainty compared to other modeled transportation assumptions (e.g., future land use patterns, traffic patterns) and then integrate the data into practice.	Develop comparisons between uncertainty in climate modeling and uncertainty in other transportation practices.

Appendix D. Glossary of Terms

Adaptation. Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects. ([FHWA Order 5520])

Adaptive Capacity. The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. ([FHWA Gulf Coast Study, Phase 1])

Capability Maturity Framework (CMF). The CMF is based on self-evaluation regarding the key process and institutional capabilities required from a transportation agency (or group of agencies) to achieve effective TSMO. This framework is adapted from a concept developed in the information technology industry called the Capability Maturity Model (CMM), which has been tailored to the transportation community. The CMF identifies the six key dimensions of process and institutional capability that directly relate to improving program effectiveness: business processes; systems and technology; performance measurement; culture; organization and workforce; collaboration. ([FHWA, Creating an Effective Program to Advance TSMO Primer])

Change Averse. A strong opposition to changing practices or beliefs.

Climate Change. Climate change refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events now and in the future. ([FHWA Order 5520])

Climate Stressor. Acute and long-term weather events and trends that have an effect on an asset or service. Among others, stressors include extreme temperature events and precipitation events, drought, sea level rise, storm surge, intense storms (e.g., hurricanes and tropical storms), strong winds, blizzards, humidity, permafrost thaw, and long-term temperature and precipitation trends. ([FHWA Gulf Coast, Phase 1])

Efficacy. The extent to which the strategy, if successfully implemented, reduces the risk. ([NYSERDA Responding to Climate Change in New York State [ClimAID]])

Emergency Management. The process of preventing, preparing for, responding to, and recovering from an emergency; where an emergency is an unexpected, large-scale, damaging event. ([TRB Regional TSMO Committee's Glossary])

Exposure. The nature and degree to which a system or asset is exposed to significant climate variations. ([FHWA, Gulf Coast Study, Phase 2])

Extreme Weather Events. Extreme weather events can include significant anomalies in temperature, precipitation and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires and windstorms (including tornadoes and tropical storms). Consequences of extreme weather events can include safety concerns, damage, destruction, and economic loss. Climate change can also cause or influence extreme weather events. ([FHWA Order 5520])

Extreme Events. For the purposes of this directive, the term "extreme events" refers to risks posed by climate change and extreme weather events. The definition does not apply to other uses of the term nor include consideration of risks to the transportation system from other natural hazards, accidents, or other human induced disruptions. (*FHWA Order 5520*)

Feasibility. How practical it is for a particular strategy to be implemented by a department, accounting for engineering, policy, legal, and insurance considerations. (*NYSERDA Responding to Climate Change in New York State [ClimAID]*)

Flexibility. Ability to make course corrections if a particular strategy is adopted. Such corrections are an essential part of adaptive management. (*NYSERDA Responding to Climate Change in New York State [ClimAID]*)

Performance Measurement. A process of assessing progress toward achieving predetermined goals. (*TRB Regional TSMO Committee's Glossary*)

Performance Measures. Indicators that provide the basis for evaluating the transportation system operating conditions and identifying the location and severity of congestion and other problems. (*TRB Regional TSMO Committee's Glossary*)

Preparedness. Actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change related damages to life, health, property, livelihoods, ecosystems, and national security. (*FHWA Order 5520*)

Projection. A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models. (*IPCC Glossary*)

Resilience. Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. (*FHWA Order 5520*)

Risk Aversion. The behavior of humans while exposed to uncertainty to attempt to reduce that uncertainty. (*Wikipedia*)

Road Weather Management. Mitigation strategies employed in response to various weather threats including fog, high winds, snow, rain, ice, flooding, tornadoes, hurricanes, and avalanches. (*TRB Regional TSMO Committee's Glossary*)

Scenario. A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions. (*IPCC Glossary*)

Scenario Planning. Scenario planning provides a framework for developing a shared vision for the future by analyzing various forces (e.g., climate change, land use, economy) that affect growth and management of the transportation system. Scenario planning tests various future alternatives in order to identify solutions that meet state and community needs under a variety of potential futures. Scenario planning is used in exercises to make critical decisions in the face of uncertainty. (*FHWA Scenario Planning and Visualization in Transportation*)

Sensitivity. The degree to which a transportation system or asset is affected by climate variability or change. (*FHWA Gulf Cost Study, Phase 2*)

Transportation Asset Management (TAM). A strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively through their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well defined objectives. (*TRB Regional TSMO Committee's Glossary*)

Transportation Management Center (TMC). The hub of a transportation management and control system. The TMC brings together human and technological components from various agencies to perform a variety of functions. (*TRB Regional TSMO Committee's Glossary*)

Transportation Systems Management and Operations (TSMO). An integrated program to optimize the performance of existing infrastructure through the implementation of systems, services, and projects designed to preserve capacity and improve security, safety, and reliability of the transportation system. (*TRB Regional TSMO Committee's Glossary*)

Vulnerability. The degree to which a transportation system or asset is susceptible to, and unable to cope with, adverse effects of climate change, variability, and extremes. Vulnerability is a function of exposure, sensitivity, and adaptive capacity. (*FHWA Gulf Coast Study, Phase 2*)

Appendix E. Sample Handout for Workshop on Climate Change Risk

This sample worksheet provides the basic format and illustrative examples for a workshop to explore climate change risk. The goal of conducting such a workshop is to develop a more complete understanding of the direct and indirect impacts and costs associated with extreme weather events. Then, this information can be folded back into practices used by the offices and departments represented at the exercise (using the approaches suggested in the guide above).

Figure 14. Photo. Flooding at Spring Mill Station on Southeastern Pennsylvania Transportation Authority's Manayunk/Norristown Regional Rail Line in Philadelphia.

Scenarios

SCENARIO 1:

[Description of local past extreme weather event. For example: *Between August 26 and September 3, 2011, Greater Philadelphia was hit with two tropical storm-force weather events – Hurricane Irene and Tropical Storm Lee. These storms brought with them torrential rainfall and strong winds across the Philadelphia region. The storms followed the wettest month (August 2011) in the region's history. The saturated ground exacerbated impacts*.]

SCENARIO 2:

[*To develop a scenario that addresses climate change risk, begin with a severe weather event familiar to the participants*.]

SCENARIO 3:

[*To develop a scenario that addresses climate change risk, begin with a severe weather event familiar to the participants*.]

Exercise

The purpose of this exercise is to develop a more complete understanding of the direct and indirect impacts and costs associated with extreme weather events by retracing the department of transportation (DOTs) response before, during, and after these events, from advance warning from the National Weather Service to resumption of normal service and everything in between. We are interested in the responses of all affected departments.

Sample Discussion Questions:

- How prepared are we for heavy rain events today?
  - When we receive advance warning of a heavy rain event:
    - At what stage (x inches of rain predicted, etc.) does your department consider escalating its responsive actions?
    - What responses are triggered?
    - What personnel are involved in heavy rain event preparations (either for actual response actions or continuity of those operations for which you are responsible)?
    - What contractors and staff are put on notice in heavy rain event preparations?
    - What materials and equipment are put on standby?
    - How are standby locations determined/prioritized?
    - Under what conditions are you concerned that you may not be adequately prepared for the event? What elements of your department are not prepared?
  - When the heavy rain event is occurring:
    - What actions are your personnel directed to take?
    - What personnel are engaged in the response?
    - At what points are contractors engaged?
    - What triggers use of materials and equipment or alternate locations?
    - What triggers decisions to discontinue service (for a particular operation or for the agency)?
  - When the heavy rain event is over:
    - What inspections/audits are conducted to evaluate impacts?
    - How are corrective actions planned?
    - How are operations resumed?
    - To what extent does "mitigation" of future impacts factor into corrective actions?
    - Do you have examples of actions that have been taken in the past after an event?
    - What "lessons learned" have emerged from past events that have not been integrated into the standard response plan?
  - What other indirect costs are associated with the DOTs response to a heavy rain event?
- What data do you collect and retain about past incidents? Based on our current responses, if heavy rain events were to occur more frequently in the future:
  - Is there new technology or equipment that you would need to be better prepared?
  - Are there specific locations within your jurisdiction that you should be increasing your planning for?
  - Would you need to change your contracting and bidding processes?
  - How could you reduce costs per event?
  - What additional workforce training would make you more prepared?
  - How can you better inform the public of disruptions?
  - What operational changes would improve your response and efficiency?
  - How can you be better prepared before an event?
  - How do you prepare to mobilize quickly for unexpected events?
  - What impact would additional events have on your equipment and assets?
  - Who should you improve coordination with and how?
  - How can you better track costs and impacts from these events?
- Background Data

[Insert data on observed weather during this event, future weather predictions, costs which can be collected ahead of the workshop, etc. All of this information will help inform the discussion.]

Appendix F. Adaptation Checklist for Technical Staff

Additional Resources

For further information on how to run an exercise of this sort, (particularly how to manage a tabletop exercise), see: http://ops.fhwa.dot.gov/publications/tabletopexercpe/tabletopexererc_pse.pdf.

The adaptation framework presented earlier in the guide provides an overview of how transportation systems management and operations (TSMO) and maintenance groups can begin to take action through steps to: define the scope of adaptation efforts; assess vulnerabilities to inform the development of adaptation strategies; and integrate climate change into decision making. The checklist that follows provides further detail on specific actions that can help move technical staff through these steps.

Define Scope

- □ Define TSMO and maintenance program goals and operations objectives that could be sensitive to climate change.
- □ Identify the extreme weather events or trends that could affect the agency's TSMO and maintenance programs.

Assess Vulnerability

- □ Catalog current capabilities (both technical and institutional).
- □ Review traffic incident reports, maintenance records, after-action reports, emergency reimbursement forms, and other sources to determine how extreme weather events have affected performance in the past.
- □ Interview staff across departments about extreme weather-related vulnerabilities (e.g., "what keeps you up at night?").
- □ Identify points and thresholds where extreme weather affects TSMO and maintenance decisions (e.g., establishing future workforce needs, weather response budgeting, setting operational objectives).
- □ Document how TSMO and maintenance practices relate to different weather thresholds (e.g., place sandbags when forecast calls for X amount of rain).
- □ Gather information on historic trends in relevant weather variables and/or how those variables may change in the future.
- □ Characterize extreme weather risks via data-driven or workshop-based qualitative or quantitative analysis.

Integrate into Decision Making

- □ Identify performance measures and targets (i.e., the acceptable level of operational performance if threat occurs).
- □ Select potential adaptation strategies (selected examples provided below – see more in Tables 6 and 8 in the guide).

Policy-based strategy examples

- □ Review and update performance measures in light of extreme weather vulnerabilities.
- □ Establish work order codes for weather events or use other methods to improve tracking of labor, equipment, and materials costs over time.
- □ Develop a strategy for incorporating weather trends in budget-setting processes.
- □ Require after-action reports with clear recommendations for improvement following extreme events.
- □ Update emergency response plans to factor in potential for greater frequency of extreme weather events.
- □ Improve cross-training across staff (including across operations, maintenance, and emergency management).

- ☐ Establish regular coordination between on-the-ground staff and other departments to discuss vulnerabilities and inform investment decisions based on past performance.
- ☐ Establish transition plans for retiring staff to maintain institutional knowledge.
- ☐ Modify current design and procurement criteria to favor durable materials and designs.

Operational and maintenance strategy examples

- ☐ Establish stand-by contracts for extreme event response.
- ☐ Improve intra-agency coordination and information sharing about conditions, closures, resources, etc.
- ☐ Enhance inter-agency coordination to promote establishment of resource-sharing agreements and information sharing about plans, initiatives, risks, and resources (e.g., include key stakeholders in routine communications to streamline process during emergency events).
- ☐ Invest in redundant communications systems and data servers.
- ☐ Expand both coverage and quality of fixed and mobile monitoring capabilities.
- ☐ Modify procurement specifications to ensure performance over a wider range of conditions.

Maintenance strategy examples

- ☐ Purchase equipment, factoring in likely future needs based on extreme weather events or climate changes (e.g., versatile equipment in Alabama to double as snow plows, mobile stockpiles of traffic control devices).
- ☐ Stockpile materials (e.g., culvert pipe, temporary bridge components, fuel) and equipment (e.g., generators, chain saws, traffic control devices) and stage them in strategic areas prior to events.
- ☐ Increase or change vegetation control practices to keep pace with climate changes (e.g., increase trimming frequency or plant more drought- or heat-tolerant species).
- ☐ Review and consider mitigating vulnerabilities when conducting scheduled maintenance activities.

Emergency management strategy examples.

- ☐ Incorporate changes in extreme event frequency into emergency management planning, including anticipated staffing, training, and equipment needs.
- ☐ Establish stand-by contracts for extreme event response.
- ☐ Conduct tabletop exercises and use routine events to drill emergency management protocols.

Adaptive management strategy examples

- ☐ Develop a system to track weather-related trends and costs over time (e.g., number of potholes repaired, snow removal costs, number of emergency event triggers, labor hours devoted to weather preparation, response, and recovery), such as through designated "weather-related" charge codes.
- ☐ Use asset management systems to track relevant information to inform decision making over time.
- ☐ Configure asset management or maintenance systems to issue alerts when vulnerable assets are due for maintenance, repair, or replacement.
- ☐ Develop and track performance metrics related to extreme weather (e.g., number/duration of weather-related road closures).
- ☐ Evaluate and select adaptation strategies based on factors such as technical and political feasibility, costs and benefits, efficacy, flexibility, and sustainability.
- ☐ Determine improvements in agency capabilities necessary for successful implementation of adaptation strategies (e.g., improvements in business processes, systems and technologies, performance management, culture, organization and workforce, and collaboration).

Monitor Progress and Revisit

- ☐ Establish a plan for monitoring and evaluating progress toward extreme weather resilience.
- ☐ Engage stakeholders needed to support monitoring and evaluation efforts.
- ☐ Monitor trends in extreme weather events and their impacts (e.g., frequency of particular events, weather-related costs and disruptions).
- ☐ Analyze data on weather trends and impacts to inform decision-making about future strategies.
- ☐ Continually revisit TSMO, maintenance, and emergency programs in light of extreme weather and climate trends.

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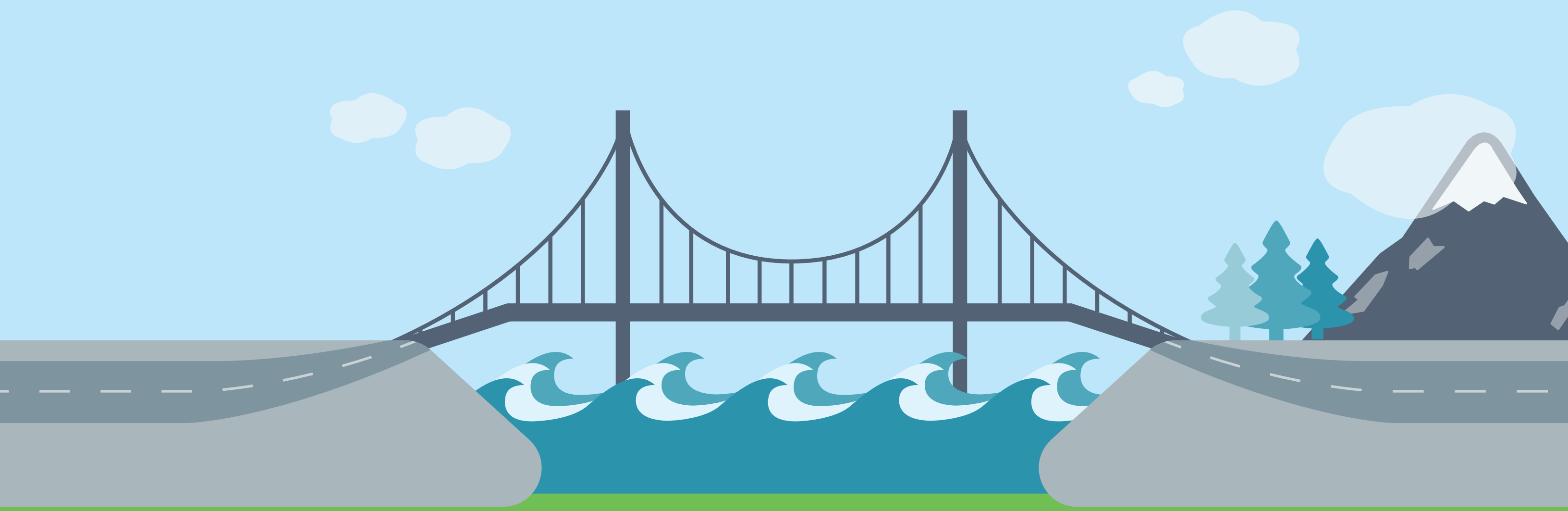

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U.S. Department of Transportation
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590
www.ops.fhwa.dot.gov
Toll-Free "Help Line" 866-367-7487