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Challenges and Opportunities for Integrating Climate Adaptation Efforts across State, Regional and Local Transportation Agencies

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TABLE OF CONTENTS

List of Tables

List of Figures

Challenges and Opportunities for Integrating Climate Adaptation Efforts across State, Regional and Local Transportation Agencies

EXECUTIVE SUMMARY

Disruptions caused by extreme weather events are imposing significant and rising costs on transportation agencies throughout the United States, and climate change is projected to increase both the frequency and severity of these events. In response, transportation agencies and organizations are exploring climate adaptation measures. This white paper presents a five-step transportation adaptation framework synthesized from common elements of an array of existing resources, and assesses the state of the practice within each of the five steps. The five steps are:

1) inventorying and monitoring transportation assets;
2) assessing climate threats;
3) evaluating asset vulnerability;
4) rating asset importance or criticality; and
5) identifying and executing adaptation actions.

The objective of establishing a common framework is to facilitate broader discussion among transportation agencies and their partners in order to identify current adaptation barriers and opportunities for interregional and interagency collaboration.

The roles for state and local agencies in implementing these steps have yet to be clearly delineated. Our review indicated implementation barriers exist in each step but can be reduced through collaboration. Because the surface transportation system functions as an integrated unit that crosses multiple jurisdictional boundaries, collaboration among state, local and regional transportation agencies is essential to maximize the efficiency and effectiveness of overall adaptation efforts, especially since many local agencies face significant resource limitations.

Key Findings

Uncertainty about emissions scenarios and the future climate conditions to design for is a major barrier to adaptation planning.

There is a need for **more robust tools** to evaluate asset criticality. Project prioritization is vulnerable to politicization.

Vulnerability assessment tools are maturing for sea level rise but are less well-developed for other threats.

Criticality is linked to vulnerability and must be assessed in full regional networks regardless of jurisdictional ownership or political boundaries.

Limited financial resources inhibit implementation of adaptation planning. It is the main limitation for the asset inventory step.

Readiness for adaptation planning varies significantly between agencies, with agencies at the local and regional level facing the most severe challenges.

Increasing interagency cooperation, especially vertical integration, will be required to maximize the efficiency of adaptation at all levels.

Workforce development needs are impacting adaptation planning.

The first step in climate adaptation planning, *inventorying transportation assets,* is conceptually straightforward and best undertaken by the agencies that own and manage transportation infrastructure. However, maintaining these databases can be costly and time consuming. Thus the biggest challenge at the state level is the resources required to develop and maintain these inventories. At the sub-state level, many smaller agencies lack the technical experience to develop asset databases. State leadership setting uniform asset database standards would facilitate the data integration required for other steps in the adaptation planning process.

The second step in climate adaptation planning is to *assess climate threats*. While many transportation agencies understand the types of climate threats they face in general terms, advances in climate modeling and model downscaling will be needed to support policy decisions and the development of new design standards. Broader consensus on the appropriate emissions/climate change scenarios to use for planning purposes, including cost benefit analysis, is also essential. Conducting climate threat assessments at the state level, likely in collaboration with partners outside the transportation sector, will provide efficiency benefits.

The third step in climate adaptation planning is to evaluate each asset's *vulnerability* to the threats identified in step two. Vulnerability is a function of the type, magnitude and probability of the climate threats. Given the uncertainties in step two, this step is technically feasible but challenging. A number of state department of transportation (DOT) officials indicated that more precise vulnerability modeling tools would be valuable and that uncertainty about the magnitude of future weather-related threats complicated vulnerability assessment.

The fourth step in the framework is to rate the relative importance or *criticality* of all infrastructure in the system. Given the resource constraints facing transportation agencies, criticality ratings are necessary in order to prioritize adaptation projects, but methods for assessing criticality are not fully developed, leaving project prioritization vulnerable to politicization. Agencies often rely on metrics such as traffic volumes that do not account for network connectivity and redundancy effects. It is clear, moreover, that criticality assessment is fundamentally cross-jurisdictional and cross-modal. National leadership is needed to develop criticality rating methods suitable for complete, multimodal, regional transportation networks.

The fifth step in the framework is to identify, select and *execute adaptation actions*. Adaptation actions can involve *infrastructure* or *processes*. Infrastructure adaptations include physical changes to infrastructure to reduce its vulnerability ("hardening"), adding infrastructure to increase redundancy, and potentially relocating or abandoning assets. Analysis of the costs and benefits of infrastructure adaptations can be challenging due to multiple temporal scales for infrastructure life and weather event return periods. Currently *process* adaptations, such as improved pre- and post-disaster response planning, are more common because they can be undertaken even with considerable uncertainty about the magnitude of future climate threats.

All steps in the adaptation planning process are iterative and interconnected. Once implemented, adaptation actions frequently impact the whole system and require ongoing monitoring and changes to asset inventories, vulnerabilities and criticality assessments.

Introduction

Disruptive events caused by weather and climate extremes are imposing significant and rising costs on transportation agencies in the United States (Meyer, Rowan et al. 2013). These events – ranging from dust storms to landslides to floods – adversely impact transportation system infrastructure integrity, reliability, level of service, and user safety. Increasingly, state DOTs, and in some cases regional and local agencies, are altering their priorities and staffing patterns to prioritize planning for severe weather events and adapting to long-term climate changes (Meyer, Rowan et al. 2013). The burden of preparing for and recovering from extreme weather events can strain the financial and human resources of transportation agencies at all levels, and the indirect costs associated with longer travel times and reduced level of service impose wider societal costs. The importance of planning for disruptive events and long-term changes has spurred numerous agencies and groups to develop resources to assist state DOTs and other transportation agencies in developing adaptation strategies to reduce the surface transportation system's vulnerability to weather extremes.

The objective of this report is to present a straightforward, five-step framework for climate adaptation planning and to use this framework to consider the challenges facing transportation agencies engaged in the adaptation process. The report is intended to summarize the state of the practice for transportation agency professionals, especially those affiliated with state DOTs, at different stages of the adaptation planning process. It is also intended to provide a simplified language and framework in order to widen the adaptation discussion and facilitate a clear delineation of the policy and research needs that must be addressed in order to advance adaptation planning. This report is based on existing published resources and interviews with transportation practitioners. Barriers to implementing the five steps include: resource constraints, workforce development needs, political constraints, uncertainty about future climate conditions, and a lack of well-developed tools for assessing the relative criticality of specific infrastructure. Broader consensus on assessment methods and probable emissions scenarios will be required moving forward. Since the transportation system functions as a unified whole across jurisdictional boundaries, ensuring that adaptation efforts are effectively implemented will require extensive collaboration among transportation agencies at all levels, and state DOTs will have a leadership role in the process. Therefore, after presenting the five-step adaption framework, this report summarizes the implementation barriers facing state DOTs for each of the five steps and then discusses the need to and opportunities for integrating regional and local agencies into the adaptation process.

Background

Recent reports by the U.S. Global Change Research Program (USGCRP) (U.S. Global Change Research Program 2014) and the International Panel on Climate Change (IPCC) (IPCC 2013) have documented ongoing changes in sea level, heat extremes and heavy precipitation events. The reports project that the frequency and severity of many extreme weather events will increase in both the medium and long term. Changing temperature, precipitation and extreme weather trends are present throughout the country, although the magnitude and direction of these trends can vary considerably from region to region. The USGCRP's National Climate Assessment (NCA) reports that average temperatures in the United States have increased between 0.7 and 1.1º Celsius since 1895 with warming accelerating since 1970 (U.S. Global Change Research Program 2014). All regions have experienced warming, especially during winter and spring seasons, but warming has been more moderate in the Southeast. Heat waves have increased in frequency throughout the country while droughts have increased in some regions. Precipitation patterns have also changed with the country as a whole experiencing both higher total precipitation and more frequent heavy precipitation events (U.S. Global Change Research Program 2014). The intensification of precipitation has been most pronounced in the upper Great Plains, Midwest and Northeast, and lowest in the Southwest. Correspondingly, the magnitude of river flooding has increased in parts of the Great Plains, Midwest and Northeast while decreasing in the Southwest (U.S. Global Change Research Program 2014). Hurricane intensity, frequency and duration have all increased since the 1980s as has the frequency and intensity of winter storms since 1950 but there has not been a clear trend in other storms such as hail, thunderstorms and tornados (U.S. Global Change Research Program 2014).

Extreme weather events linked to the trends documented in the NCA can shut down or compromise components of the surface transportation system for short or prolonged periods of time. While some projected climate trends also offer benefits to the transportation sector, such as a longer construction season in some parts of the country, the potential harms and benefits of climate changes are asymmetrically distributed, with significantly more, and more severe, negative effects than positive ones. Consequently, transportation practitioners are exploring how to adapt the transportation system and associated management processes to lessen the impact of these extremes. Some agencies are actively pursuing adaptation planning efforts. These agencies tend to be in places that have experienced a recent significant event, such as the Vermont Agency of Transportation, or that have participated in Federal Highway Administration (FHWA) pilot programs such as the Washington Department of Transportation. Other agencies are just beginning, or have not yet begun, their climate planning efforts because of other priorities (in some cases climate mitigation), limited resources, minimal projected impacts in their region, or political skepticism toward climate change.

Since climate adaptation and climate mitigation efforts are frequently discussed together, it is worth clarifying their definitions. In its Fifth Assessment Report, the IPCC (IPCC 2014) defined climate adaptation as the "process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploits beneficial opportunities." In this paper, climate adaptation is discussed in terms of the process of adjusting the transportation systems (both the physical infrastructure as well as processes for planning, management and operations) in response to current and projected climate and extreme weather conditions to moderate the adverse impacts on short-term and long-term system performance. This paper focuses specifically on the highway system but many of the impacts and adaptation processes highlighted here have implications for air, rail and water infrastructure. On the other hand, mitigation is defined in the same IPCC report (IPCC 2014) as "human intervention to reduce the sources or enhance the sinks of greenhouse gases."

Mitigation and adaptation efforts may be synergistic or antagonistic to one another. Many "green infrastructure" measures, for example, advance both mitigation goals (by acting as carbon sinks) and adaptation goals (by absorbing precipitation and reducing flooding impacts). In contrast, efforts to improve system redundancy by adding alternative routes as an adaptation strategy may also result in increases in travel and greenhouse gas emissions.

Impacts of Climate and Extreme Weather Events on the Transportation System

The precise challenges that extreme weather events pose to the transportation system vary considerably from region to region, in their severity and in the duration of the disruptions that they cause. Impacts vary among modes and depend on infrastructure conditions and design characteristics. The stages of an extreme weather disruption in the transportation system are illustrated in Figure 1. Some events can be forecast in advance and this warning period provides a window to prepare for these events while other events occur with minimal or no warning (Stage A). The warning period can vary from days to months or even years depending on the event type. The warning time for sea level rise is on the scale of years and decades. Flooding or drought linked to seasonal precipitation levels may be predicted weeks or months in advance. The Missouri River floods in 2011, for example, were in large measure the result of near-record snowfall and the risk of flooding was recognized months in advance of the flood itself (NOAA 2012). Coastal and river valley flooding, in contrast, may happen with comparatively little warning. Forecasts for Tropical Storm Irene in Vermont in 2011 and Hurricane Sandy in the New York/New Jersey region in 2012 preceded the storm by only days. Dust storms and landslides can occur without any warning. In some cases, agencies may preemptively close parts of the transportation system to facilitate preparation for or faster recovery from an event (Stage B).

Similarly, the durations of the events themselves (Stage C) and of the recovery periods (Stage D) associated with them are highly variable. Some events, such as dust storms, which are linked to heat waves and drought conditions, last only minutes or hours. Dust storms can cause road and airport closures due to low visibility conditions during the storm, but they typically do not significantly damage infrastructure, and the recovery time after these events pass is minimal. In contrast, some types of flooding events can last for weeks and can destroy roads, bridges and other infrastructure. In these cases, the recovery period can last for months or even years.

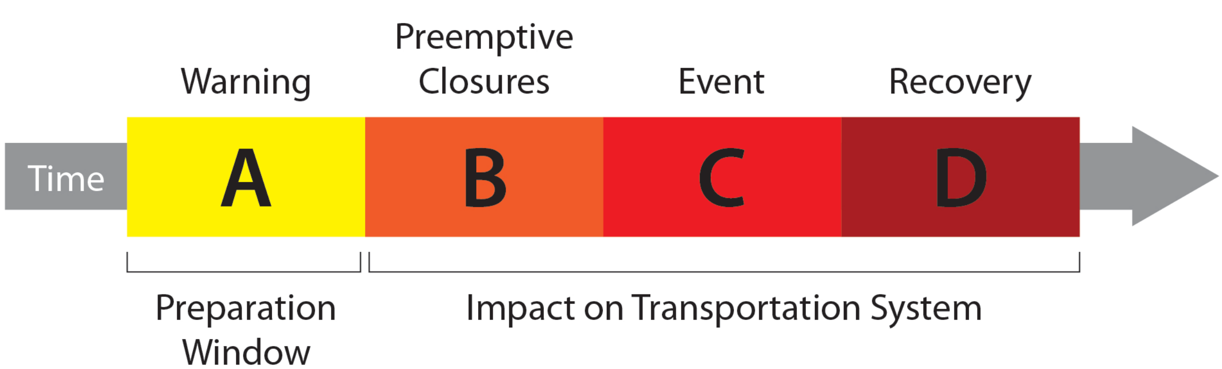

Figure 1: Stages of Extreme Weather Disruption

The examples in the sidebar at right (letter and color codes are taken from Figure 1) illustrate how much variability there is in the duration of each stage of a disruption. As these examples make clear, the recovery period is the longest stage in the disruption for many event types.

The direct impact of a given event reflects a combination of the advanced warning of the event, the event duration and the recovery period for the event. Adaptation planning needs to consider measures that increase agencies' capacity to take advantage of the preparation window, minimize the damages sustained during the event itself and facilitate a rapid recovery period.

In addition to the direct impact that these events have on the transportation system, some events cause changes to the natural or built environment that elevate the risk for future disruptions. For example, though forest fires do not tend to cause major damage to transportation infrastructure, fires reduce vegetation cover and char the ground, significantly raising the risk of subsequent flash flooding and mudflows.

Considering the variety of events that impact the transportation system, transportation professionals must consider a host of different adaptation actions, ranging from changes in maintenance and communication procedures to changes in infrastructure design and even the relocation or replacement of infrastructure. The importance and complexity of this work is spurring a rapid expansion of new

Selected Extreme Weather Disruptions

Missouri River Flooding – Iowa (2011)

Six Months Total:

A – Heavy winter snow cover provides an early *warning* of elevated flooding risk. (Winter/spring 2011).

C – Flooding washes out four miles of I-680 and inundates sections of I-29. The interstates remain flooded for over a month. (June – July/2011)

D – Interstate 680 reopens, ending a *recovery period of more than three months.* (11/2/2011)

Tropical Storm Irene – Vermont (2011)

Four Months Total:

A – Irene reaches hurricane strength in the Caribbean a week before making landfall in New Jersey. (8/21-28/11)

C – Seven inches of rain results in extensive flooding, closing 321 roads, 124 bridges and isolating 11 communities in Vermont. (8/28-29/2011)

D – All state facilities are re-opened after a four-month recovery period. Over 40 town bridges remain closed.

Dust Storm – Oklahoma (2012)

Less Than One Day Total:

C – A large dust storm causes near blackout conditions and a multi-vehicle accident on Interstate 35.

D – The Interstate remains closed for several hours after the storm abates as accident debris is cleared from the roadway. (10/18/12)

Hurricane Sandy – New York/New Jersey (2012)

Seven Months Total:

A – Hurricane Sandy forms in the Caribbean. Several states declare states of emergency. (10/22-27/14)

B – Amtrak, MTA subway, commuter rail and bus services close preemptively ahead of landfall. (10/27-28/12)

C – Hurricane Sandy makes landfall in New Jersey. The storm duration in the New York/New Jersey area lasts for 24 to 48 hours. (10/29-30/12)

D – Service is restored for the A Train from Long Island to Manhattan, one of the last stages in a recovery period lasting for seven months. (5/30/13)

Oso Landslide – Washington (March 2014)

Six Months Total:

C – A massive landslide in Snohomish County inundates State Route 530. The event duration is only one minute. (3/22/14)

D – State Route 530 reopens to two-way traffic concluding a six-month recovery period. (9/27/14) adaptation tools and numerous pilot projects.

Efforts To Support Adaptation Planning For Transportation Agencies

Developing adaptation guidance and strategies has become a key initiative for many transportation organizations. In recent years, the American Association of State Highway and Transportation Officials (AASHTO) (Meyer, Rowan et al. 2013) and the Association of Metropolitan Planning Organizations (AMPO) (Resource Systems Group 2008) have both convened climate adaptation meetings to facilitate information exchange, share best practices and determine what data and tools are needed to respond to weather extremes. The FHWA and the Federal Transit Administration (FTA) have also been very active in this arena. The FHWA developed a conceptual Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2012) and funded five state and local transportation agencies to pilot the application of this tool in 2010. A second round of 20 pilot projects, launched in 2013, are now nearing completion. The FTA has also funded several adaptation pilots. The Transportation Research Board (TRB), through the National Cooperative Highway Research Program (NCHRP), has issued synthesis reports on both climate (Meyer, Flood et al. 2014) and extreme weather (Baglin 2014). Other agencies such as National Oceanic and Atmospheric Administration (NOAA) and the Federal Emergency Management Agency (FEMA) are developing resources to help inform adaptation efforts. The Presidential Task Force on Climate Preparedness and Resilience has been charged to provide recommendations to remove barriers to investment in resilience, including in the transportation sector (Office of the Press Secretary 2013).

Many of these resources are available through Georgetown Climate Center[1] (GCC) Adaptation Clearinghouse. The Clearinghouse also includes 100 community case studies, developed by the Center as part of a cooperative agreement with FHWA. All resources are categorized by type (assessments, funding, law and governance, planning and solutions), location and climate threat. The number or resources and categorizations themselves speak to the complexity of the issue as faced by state and local planning agencies. The complexity has resulted in much of the work to date taking the form of case studies and synthesis reports.

In addition to these valuable case studies and synthesis reports, several specific tools have recently been released by FHWA. These include a tool to capture downscaled climate data from the Coupled Model Intercomparison Project (CMIP), the Vulnerability Assessment Scoring Tool (VAST), and an interactive version of the Climate Change and Extreme Weather Vulnerability Assessment Framework.

As indicated in Table 1, a large number of organizations are active in the adaptation arena. Their exact role and mission in promoting transportation sector adaptation is still evolving and several of the transportation officials interviewed for this report indicated that the sheer volume of information they produce can be overwhelming. There are extensive efforts underway to promote information exchange and to develop planning frameworks and tools.

[1] www.georgetownclimate.org

Significantly fewer organizations are developing climate and weather forecasts suitable for establishing design standards.

Table 1. Organizations and Agencies Active in Transportation Sector Climate Adaptation

Organization	Activities			
	Developing Frameworks & Tools	**Infrastructure Data Collection**	**Climate/Weathe r Forecasts**	**Facilitating Exchange**
AASHTO				X
FEMA			X	
FHWA	X			X
FTA	X			X
NCHRP				X
NOAA			X	X
State DOTs	X	X		X
MPOs		X		X
Counties, cities, towns		X		
Universities, NGOs and research institutes	X	X	X	X

Methods

In order to assess the obstacles to the successful implementation of adaptation strategies, this paper combines a review of adaptation publications by FHWA, FTA, AASHTO and others with findings from standardized, open-ended interviews of transportation practitioners in state DOTs, Metropolitan Planning Organizations (MPOs), city government, non-governmental organizations, and research institutions. Based on this review, we identified common steps used in most adaptation processes. To assess current obstacles to adaptation efforts, particular attention was paid to lessons learned from the first round of pilot adaptation projects supported by the FHWA – Washington DOT (WSDOT 2011), Virginia DOT (VDOT 2011), New Jersey TPA (NJTPA 2011), Metropolitan Transportation Commission – San Francisco Bay Area (Nguyen, Dix et al. 2011), and the Oahu Metropolitan Planning Commission (SSFM International 2011). In addition, we conducted interviews with nine state agencies, six MPOs and local agencies, and four transportation NGOs or research institutions. All interviews were conducted by telephone by the same individual using a structured question format. The agencies were distributed across five of the six continental climate regions identified in the National Climate Assessment. In evaluating the implementation potential of the adaptation framework for state DOTs, we highlight common themes that arose across multiple interviews; given the occasionally sensitive nature of these comments, however, we do not attribute these findings to individual agencies. We subsequently touch on the role of regional and local agencies in climate adaptation and the unique challenges and opportunities these agencies face.

It is important to note that in our interviews, we encountered practitioners who stated that climate change was not a concern or that the political climate in their jurisdiction made it difficult to discuss issues related to climate change. Consequently, several of the interviews focused less explicitly on "climate change" and more on resiliency, emergency preparedness and extreme weather hazards. Our interview sample was not large enough to indicate whether this political constraint was correlated with adaptation activity. Instead, we observed that agencies in regions that had experienced extreme weather disruptions to the transportation system, including longstanding hurricane risks, were more advanced in their planning than regions that had not experienced disruptive events in the recent past.

A Five-Step Common Framework

Several groups have developed adaptation guidance and frameworks for identifying adaptation needs (FTA 2011, FHWA 2012, Meyer, Flood et al. 2014). Broadly speaking, these documents, as well as several international adaptation protocols (Wall and Meyer 2013), outline similar processes for assessing adaptation needs though with some differences in terminology and different groupings of actions. The FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2012) is fairly typical of these documents and actually includes steps that precede as well as follow the vulnerability assessment, although it goes into relatively less detail about these components of the adaptation process. It has gained considerable traction with DOTs and MPOs through the FHWA's pilot program to test the framework with state and local agencies. This framework (Figure 2) presents an iterative process of collecting infrastructure and climate data, assessing asset sensitivity, an optional assessment of risk, a vulnerability rating, and optional criticality rating that feeds into monitoring and integrated decision making. The framework was also adopted by

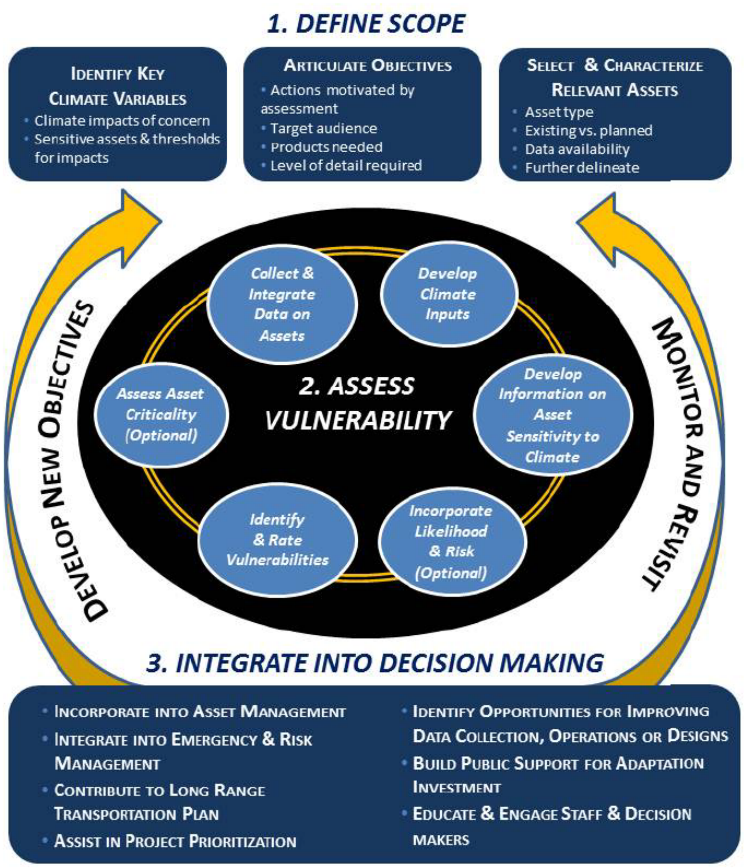

Figure 2. The FHWA's "Climate Change and Extreme Weather Vulnerability Assessment Framework" from (FHWA 2012).

the FTA (FTA 2011). The adaptation framework that appears in NCHRP's *Practitioners Guide* (Meyer, Flood et al. 2014) includes many of these same steps plus several steps devoted to identifying, assessing and implementing adaptation strategies.

For the purpose of evaluating barriers to climate adaptation, we have drawn five key steps in the adaptation planning process from other frameworks (Figure 3):

1) inventorying and monitoring the system assets;
2) assessing climate threats;
3) evaluating asset vulnerability (given the asset conditions and climate threats identified in steps 1 and 2);
4) rating the importance or criticality of each asset to overall system performance; and
5) identifying and executing adaptation actions to reduce adverse impacts based on the vulnerability and criticality evaluations.

The adaptation process is continuous and non-linear with important feedback mechanisms, as represented by the arrows in Figure 3. For example, adaptation actions themselves are designed to reduce vulnerability but may also change the asset inventory in ways that affect not only the vulnerability of the altered asset but also the criticality of multiple assets in the system. Additionally, many of the steps do not need to be completed sequentially or are conducted in an ongoing and iterative manner. Assessing climate threats, for example, is independent of criticality rating steps. Inventorying and monitoring assets must happen on an ongoing basis to support the evaluation of adaptation actions. Finally, the adaptation process is embedded in a larger social context with a wide variety of actors and stakeholders. Changing understanding of the issues may lead to a redefinition of the problems facing the transportation sector and consequently the solutions that are available to transportation agencies (Moser and Ekstrom 2010).

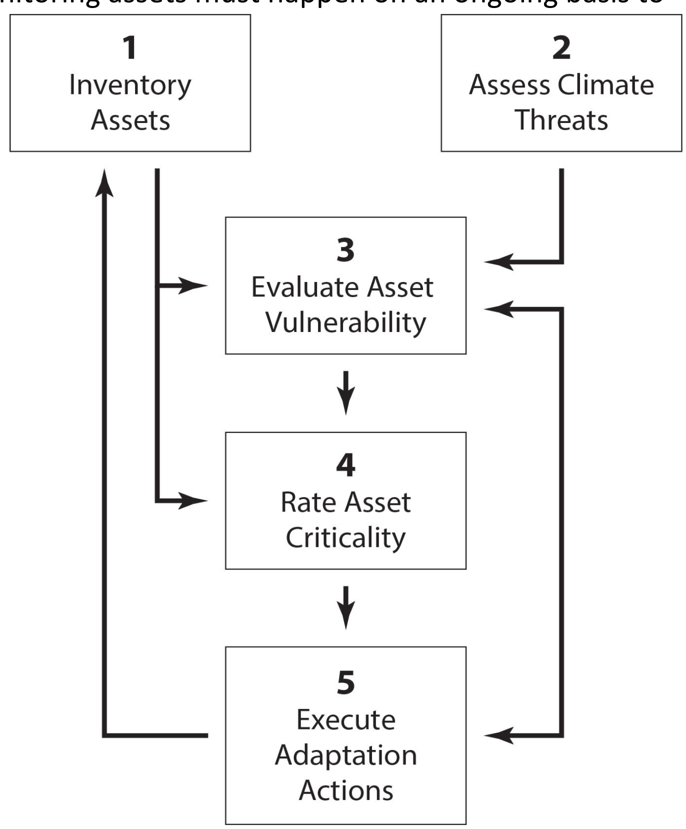

Figure 3. Five-step Common Framework for Climate Adaptation Planning for Transportation Systems.

Implementing each of these steps represents different challenges to transportation agencies. In some cases, these challenges are related to resource constraints. In other cases, data limitations or conceptual uncertainty can pose significant challenges. Objective methods for rating criticality are still not well-developed, so the criticality rating component requires improvements in methods that are best developed at a national level. Assessing climate threats is subject to considerable uncertainty in long-term emissions trends and therefore in climate forecasts. The selection and execution of adaptation actions is hindered by the limitations inherent in each of the proceeding components. For some steps, the expertise, data and methods needed to complete the step are found completely within DOT agencies. Other steps require cooperation and exchange with other agencies that may have different priorities and missions. Table 2 outlines the current capacity of leading state DOTs to implement each of the steps in the adaptation process as expressed in our interviews and the reviewed literature. The actual capacity of DOTs varies from state to state and the challenges within each of these steps are discussed in more detail below.

Table 2. Capacity of State DOTs to Implement Adaptation Framework Components

Step	Conceptual Understanding	Adequacy of Tools and Data	Challenges
Inventory and Monitor Assets	High	Moderate to High: Asset management tools offer a solid base for comprehensive asset inventories. Data quality is highly variable across agencies and jurisdictions.	Funding and time constraints to populate and maintain databases
Assess Climate Threats	High	Poor to Moderate: Tools for modeling climate are increasingly sophisticated but appropriate inputs for these tools are uncertain. The spatial and temporal resolution of these tools remains limited.	Uncertainty with regards to emissions scenarios; further development of down scaling methods
Evaluate Vulnerability	High	Poor to High: Vulnerability modeling is dependent on climate inputs. Modeling tools are better for sea level rise than other climate threats.	Quality and resolution of future climate data
Rate Asset Criticality	Moderate	Poor: Quantitative/comprehensive tools have not yet been developed.	Lack of consensus on methodology; politicization
Select and Execute Adaptation Actions	Moderate	Tools are *poor to moderate* for *infrastructure* actions (vulnerability output lacks the resolution needed by engineers for design purposes) but *high* for *process* adaptations.	Limitations in prior steps; lack of data for design standards; challenges in cost-benefit analysis; funding

Inventorying and Monitoring Assets

The first component of the common framework is to inventory and monitor system assets. Without an understanding of the assets that compose the system, including the condition and functional and physical context of each asset, it is impossible to determine these assets' vulnerability or criticality (steps 3 and 4). Condition data is important in assessing an asset's vulnerability to extreme events. Physical context such as surrounding slopes, land use, proximity to water, and soil type all influence how weather events impact the infrastructure. Traffic or operational capacity is one component that significantly affects asset criticality. In order to maximize the usefulness of the inventory, all data must be routinely maintained and updated so that vulnerability and criticality assessments can be kept current as well as to evaluate adaptation actions once they have been implemented. All records need to be digitized and spatially explicit so that they can be easily accessed and integrated with other data sources.

The requirements for asset inventory are well-understood within the transportation community. State DOTs have experience maintaining inventory and condition databases for asset and maintenance management systems. For example, data collected for the National Bridge Inventory Program (Meyer, Rowan et al. 2012) includes bridge latitude and longitude and information about its condition that could be integrated with additional variables (such as elevation above the water) into adaptation planning (NJTPA 2011). Many states also have culvert inventories and pavement condition monitoring systems that require similar systems and skills to maintain (Meyer, Rowan et al. 2012, Meyer, Flood et al. 2014). Asset inventory requirements for state DOTs are also increasing as part of Moving Ahead for Progress in the 21st Century Act (MAP-21), but states are just beginning to implement these requirements. States are mandated to include a summary listing of all bridge and pavement assets that are part of the National Highway System (NHS) in the asset management plan, and encouraged to include all infrastructure assets within the highway rights-of-way (FHWA 2014).

In spite of the clear understanding of the asset inventory process, few states have undertaken systematic asset inventories adequate for adaptation planning (Meyer, Flood et al. 2014). During the interviews conducted with transportation professionals, several state DOT officials expressed concern about the implementation of comprehensive asset inventory programs. These concerns largely revolved around the financial and personnel costs associated with establishing and maintaining an accurate inventory – a challenge that grows as asset inventories become more comprehensive and include the additional variables needed for adaptation. For example, many states currently maintain culvert inventories but only for culverts above a certain size threshold (Meyer, Flood et al. 2014). As extreme weather events become more frequent, however, smaller culverts are at increased risk of failure and the value of including these culverts in the asset inventory increases. Even for data that states already collect, integrating disparate data sources is often a significant difficulty. As part of the FHWA's Climate Change Resilience Pilot program, Washington State DOT (WSDOT) sought to bring together data from a variety of state sources, but this proved to be considerably more difficult than the WSDOT team anticipated (WSDOT 2011). This step of the adaptation framework is conceptually straightforward but it can be difficult and costly to implement.

To lessen the burden associated with the inventory portion of the framework, several agencies engaged in adaptation efforts looked for ways to reduce the assets that need to be included in the asset inventory. The FHWA suggested limiting assets by type (FHWA 2012) while the Oahu MPO and the San Francisco MPO preselected assets based on expert knowledge of system criticality (Nguyen, Dix et al. 2011, SSFM International 2011).

In short, state DOTs have the technical capacity to undertake comprehensive asset inventories. The major barriers to accomplishing this are the financial and personnel resources required.

Assessing Climate Threats

Both the IPCC and the U.S. Global Change Research Program have released updated reports that layout current and projected regional climate trends (IPCC 2013, U.S. Global Change Research Program 2014). The National Climate Assessment provided information about general regional trends in climate and extreme weather for the United States. These documents are useful for understanding the types of events that states are dealing with currently and provide general indications of future threats. The documents also provide a sense of the general impacts that these threats might have on the transportation system. It is clear, for example, that current climate trends have already resulted in increased precipitation frequency and intensity across much of the United States as well as more prolonged heat waves and drought in other parts of the country. The state DOT officials interviewed were aware of the general weather extremes of greatest significance to their states but also stated that they needed more geographically specific, higher resolution climate/weather data, explicit design standards and guidance on what emissions scenarios to consider.

General trends lack the specificity required to evaluate individual asset vulnerabilities and to establish the specific adaptation actions necessary to adjust to current climate extremes, let alone to establish design standards for infrastructure with a multi-decade life expectancy. In order to improve the management of current extremes, NOAA is updating the Precipitation Frequency Atlas (NOAA) while FEMA is updating its Flood Insurance Rate Maps see e.g. (FEMA 2013). While these resources are valuable, the updating process is slow and the updates reflect only current climate conditions that could be outdated within the lifetime of some transportation assets. Managing the transportation system for future climate threats is more difficult because of uncertainty about future emissions, the accuracy of global climate modeling and the adequacy of the spatial and temporal resolution of downscaled data. Respondents expressed that longer term global climate projections need to be downscaled to produce forecasts that are usable for design of specific infrastructure and adaptation actions at the regional scale. Downscaled climate data is not yet widely available and some important variables, especially precipitation at the watershed level, are very difficult to model (NJTPA 2011). The FHWA's recently released CMIP Climate Data Processing Tool provides practitioners with a simplified interface for interacting with data from the U.S. Bureau of Reclamation's Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections, which will facilitate access to regional data. This tool outputs downscaled precipitation and temperature statistics and represents a valuable advancement for the transportation community. However, additional outputs are still required, such as precipitation intensities in time increments smaller than 24 hours and resulting peak hydrological flows. In addition, policy decisions related to the appropriate emissions scenario to use for adaptation planning will be needed in order to establish design standards and conduct cost benefit assessments for adaption actions.

Given the uncertain magnitude of future climate threats, several of the DOT officials interviewed emphasized the possibility of focusing on adapting the highway transportation system to be more resilient to current weather impacts. Many cited recent experience with extreme weather events and trends in the disruptive events as the basis for their adaptation efforts. Several of these agencies are focused on collecting and updating data about current climate conditions. Given this experience, it is unsurprising that the states contacted that were least actively engaging with adaptation issues had experienced relatively little change in weather and few extreme events. Asked about other states that might serve as sources of useful information, most DOT officials responded by pointing to immediately neighboring states and to states in the FHWA or FTA pilot assessments. Focusing on current climate conditions and drawing lessons from neighboring states are both sensible approaches given the time and resource limitations facing state DOTs. In the longer term, however, it may be important to expand these efforts to include a more comprehensive analysis of future conditions and to draw lessons from a wider set of states.

Several of the agencies participating in the FHWA pilots also noted the urgent need for better downscaled climate data (SSFM International 2011) or opted to use scenario-based approaches to characterize climate threats due to the challenges and uncertainties involved in projecting future climate conditions (NJTPA 2011, VDOT 2011). The WSDOT (WSDOT 2011) pilot project is notable for its use of downscaled climate data provided by the University of Washington's Climate Impact Group.

Ultimately, state DOTs should not and will not be solely responsible for developing the climate and extreme weather scenarios and standards that drive adaptation actions. Developing climate models that output the information needed by transportation engineers and planners will require collaboration among state agencies, among federal agencies and between state and federal agencies. In addition, the selection of the climate scenarios to prepare for reflects a social tolerance for risk and therefore will require public input to inform policy decisions. As noted in Table 2, the conceptual understanding of the climate threat step is high, but the adequacy of tools and data, while improving, is still poor to moderate.

Evaluating Infrastructure / Asset Vulnerability

The FHWA adopted a definition of vulnerability as the degree of susceptibility to adverse effects of climate change and defined susceptibility as "a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (FHWA 2012). As discussed above, the probable magnitude of future climate threats remains a source of uncertainty that inhibits vulnerability evaluations. Vulnerability assessments for some climate threats, such as determining how susceptible infrastructure is to inundation, is a comparatively straightforward engineering analysis, but assessing infrastructure sensitivity to other climate threats is less straightforward. During the interview process, a number of DOT officials indicated that more concrete vulnerability modeling tools would be valuable and that uncertainty about the magnitude of future hazardous climate conditions and extreme events hindered the vulnerability assessment phase of adaptation planning. Since an asset's vulnerability depends upon the severity of the extreme events that it is exposed to, uncertainty about the magnitude of these events necessarily adds uncertainty to the vulnerability assessment. Better probabilistic forecasts of the magnitude of future events, especially of events that can cause sudden infrastructure failure (such as precipitation and storm intensity), would improve agencies' capacity to undertake the vulnerability step of the adaptation planning.

Given these constraints, some DOTs are relying on experienced practitioners to identify historically vulnerable infrastructure. Outputs from these efforts include mapping the location of past infrastructure failures due to flooding, landslides and other weather related disruptions. This represents a good start and, in the short run, this approach may be advantageous because it leverages existing expertise and focuses attention on infrastructure with demonstrated vulnerability to past conditions. In the long run, however, this approach may fail to identify infrastructure that could be highly vulnerable under uncertain, variable and seemingly unpredictable future conditions. Failure to anticipate new and evolving vulnerabilities could have dramatic, adverse effects on system performance.

One area where assessing vulnerability is more advanced is for sea level rise and inundation scenarios, a major focus of the first round of FHWA vulnerability assessment pilots. Modeling for the San Francisco Bay MTC pilot, for example, looked at combined effects of sea level rise and extreme tides but did not consider inland flooding impacts from increased precipitation intensity and riverine overbank flooding (Nguyen, Dix et al. 2011). In other pilot studies and at several of the agencies that were included in our interview process, vulnerability was primarily assessed qualitatively using expert knowledge from within the state and local agencies (SSFM International 2011, WSDOT 2011). Many of the second round of FHWA pilots are focused on threats other than sea level rise and may help to produce vulnerability modeling tools for a wider range of threats. The FHWA's Excel-based tool, VAST, provides an indicator based framework for considering infrastructure vulnerability (ICF International 2014). While this tool provides an organized framework for considering indicators of vulnerability, it does not include an objective rationale for the weighting of these indicators. Currently, as indicated in Table 2 although conceptual understandings are high, the data and tools supporting efforts to evaluate vulnerability are variable and may or may not be identifying the vulnerabilities that are most important for overall adaptation planning.

Rating Infrastructure / Asset Criticality

Because resources available for adaptation actions are limited, adaptation actions, especially those related to physical infrastructure, must be prioritized. The FHWA Framework and others suggest prioritization of adaptation actions based on a combination of asset vulnerability and asset criticality. Methods for measuring criticality that incorporate full network analysis and all regional infrastructure, however, are not well-established. Failure to fully consider all components of the system could result in erroneous prioritizations, even with perfect analytical tools.

Many DOTs reported difficulty with the criticality assessment phase and several also reported that the prioritization process could become politicized. DOTs working to assess criticality relied on expert judgment or metrics such as Average Daily Traffic (ADT), roadway functional class, importance to freight traffic, and status as an evacuation or lifeline route. The San Francisco Bay Area MTC considered the role of roadway embankments in limiting the spread of inland inundation (Nguyen, Dix et al. 2011), an example of the protective capacity that infrastructure can provide. Since assets that provide this type of protection prevent the serial failure of other assets, protective capacity is important to consider when rating asset criticality. Table 3 summarizes factors that contribute to asset criticality during routine and emergency system operation. None of the agencies that participated in the interview process or completed the first round of FHWA pilots used all these factors and there is not yet a consensus on which factors to consider. Methods to incorporate multiple factors and modes are not fully developed.

Table 3. Factors Contributing to Asset Criticality

Traffic Volumes and Proxies: • Average Daily Traffic (ADT) • Functional class • Surrounding population	**Connectivity Measures:** • Availability of alternate routes • Evacuation routing • Access to important destinations (e.g. hospitals)
Protective Capacity: • Asset functions as a barrier to protect other critical infrastructure • Asset functions as a conduit or diverter of damaging flows of water/other elements	**Non-systematic Factors:** • Replacement cost • Historic/cultural significance • Political considerations

Conceptually, many DOT officials understand that, despite wide-spread use, traffic volumes (or proxies), are not a sufficient metric by which to assess criticality and that, at a minimum, route redundancy needs be considered in conjunction with volume measures. Several approaches to quantifying criticality that account for traffic volumes and the redundancy inherent in the network layout are based on modeling the total travel delay caused when the capacity of a road segment or link is disrupted or removed. This approach is the basis for a number of studies that look at single link disruptions as a means for assessing criticality and robustness (Jenelius, Petersen et al. 2006, Scott, Novak et al. 2006, Erath, Birdsall et al. 2009, Sullivan, Novak et al. 2010). Phase II of the FHWA's Gulf Coast study (ICF International 2011), also used this approach but only assessed the criticality of a small set of "representative" links which are unlikely to accurately capture the full typology of the network. Two primary shortcomings of this method, as applied in these examples, are that they assess criticality based only on single link disruption and that the models typically include only main road links, not the whole road network, even though smaller local roads may provide important functional redundancy. Since extreme weather events have the capacity to disrupt multiple links simultaneously, this approach may overstate the security of the system's redundancy and identify incorrect links as most critical. Recent work has begun to consider area, rather than single link, disruptions (Jenelius and Mattsson 2012) but it is unclear how realistically these areas represent actual infrastructure vulnerability. Thus, to most accurately measure the criticality of a link, it is important to consider not just the availability of alternate routes but the vulnerability of those alternate routes. Note that the FHWA uses criticality as a component of the vulnerability measure but the approach that we are suggesting requires that vulnerability be assessed prior to assessing criticality.

The appropriate methods for assessing criticality may also vary over different temporal and spatial scales. Temporally, the criticality of some infrastructure may vary with the length of the disruption depending on the destinations to which the infrastructure provides access. For example, a link that provides access to employment centers might be considered highly critical in the context of vulnerability to sea level rise that could permanently impact that link's capacity. The same link might be considered less critical for short-term disruptions such as those caused by extreme winter weather or hurricanes. In contrast, links to hospitals would be considered highly critical even for short-term disruptions. Moreover, the infrastructure that is most important for emergency service during and immediately after an extreme weather event may not be the same as the infrastructure that is most important to normal traffic operations. In terms of geographic scale, freight corridors can cross several states and thus their overall economic importance may not be evident at some scales of analysis. When measuring criticality it is extremely important to define the space, time and type of event that are being considered.

In summary, methods to establish criticality are currently limited and a lack of consensus on what factors to include or how to weight these factors relative to one another can lead to highly subjective criticality rankings. Development of better methods for criticality assessment is necessary and an area for national organizations and academic institutions to provide leadership. As suggested by Table 2, the rating of criticality may be the weakest link in the common five-step framework.

Identifying and Executing Adaptation Actions

As is shown in Figure 2, identifying and executing adaptation actions depends on the steps that precede it in the adaptation process. Moreover, given the wide variety of climate impacts that are expected to affect the transportation system, a state DOT can see adaptation benefits from a wide range of actions, including strengthening infrastructure so that it is less vulnerable to particular events (often referred to as infrastructure hardening), relocating built infrastructure so that its exposure to particular events is reduced, altering land use patterns, improving pre- and post-disaster response planning, and budgeting for increased maintenance costs. Green infrastructure adaptation efforts, which manage vegetation and natural areas to moderate weather impacts, have been shown to provide other co-benefits (Foster, Lowe et al. 2011). Actions with co-benefits that justify the cost of a project before considering the adaptation benefits are often termed "no regrets" strategies since society benefits regardless of the climate and extreme weather outcomes. These projects may be limited in number and in most cases calculating realistic cost benefit ratios is complicated by variable infrastructure life expectancies, uncertainty about projected planning timeframes and unknown weather event return periods. The transportation chapter of the NCA characterized potential adaptation actions as either strategies that reduced the impact of extreme events (e.g. infrastructure hardening) or strategies that reduce that consequence of extreme events (e.g. updating evacuation/contingency plans) (U.S. Global Change Research Program 2014).

It is useful to further divide adaptation actions into either process or infrastructure adaptation actions. Looking at adaptation actions through this lens reveals that many process adaptation actions can be undertaken even with considerable uncertainty about the magnitude of climate threats and the specific vulnerabilities that they will cause. In contrast, infrastructure adaptation actions are considerably more costly and require greater certainty in terms of vulnerability or criticality to implement with confidence.

Process adaptations, which generally reduce the consequences of extreme events, include the following actions:

- improving communications procedures;
- including climate risk in planning processes;
- developing hazard mitigation and emergency response plans;
- changing maintenance schedules and practices; and
- improving monitoring and data collection.

Adjustment of maintenance schedules or practices is one of the few process adaptations that can reduce the impact of extreme events, rather than just their consequences. Increasing the frequency of culvert clearing activities, for example, can reducing flooding when extreme weather events do occur. Many of the state DOT officials interviewed are currently implementing at least one of these process adaptations. Because process adaptations are generally lower in cost and can offer benefits that translate regardless of the magnitude of extreme events, these actions are also cited as best practices in recent AASHTO (Meyer, Rowan et al. 2013), FHWA (ICF International 2013), and NCHRP (Baglin 2014) synthesis reports.

Infrastructure adaptations include strengthening and protecting infrastructure, enhancing redundancy and abandoning vulnerable infrastructure (FTA 2011). Given uncertainty about future conditions, DOTs could also opt to build lower cost infrastructure that is designed to be replaced more frequently rather than undertaking the hardening effort required to withstand all potential extreme weather scenarios. Many of the DOT officials interviewed stated that identifying and implementing infrastructure adaptation actions was a “next step.” Those few infrastructure adaptations that are underway tend be low cost or to serve multiple purposes and to be considered “no regrets” projects. Relatively, low cost measures include options like raising subway vents to prevent flooding of subway tunnels. Multipurpose actions include building larger bridges to facilitate fish and wildlife passage that simultaneously improves resilience to flooding events. In contrast to process adaptation, infrastructure adaptation tends to be costly and to require significant planning processes and a degree of certainty with regards to climate threats and cost benefits that is currently very challenging.

At this time, the conceptual understanding of adaptation actions is moderate (Table 2) and actively increasing. However, the adequacy of tools and data varies significantly. Progress on process changes is advancing rapidly in some places, but the tools and data to guide large-scale infrastructure adaptations are inadequate, mainly due to reliance on output from prior steps in the framework.

Integrating Local and Regional Agencies

While the states and federal government provide approximately 70% of all surface transportation funding (Rall, Wheet et al. 2011), towns, municipalities and counties own more than 75% of all road miles and nearly 50% of all bridges in the United States (FHWA 2012b). Consequently, many of the effects of extreme weather events impact locally owned and managed transportation infrastructure, and adaptation planning must incorporate local and regional agencies and infrastructure. To date, there is considerable variability in the level of engagement in adaptation by local and regional transportation agencies with existing efforts concentrated in large, coastal MPOs and municipalities as well as those that have received FHWA or other external funding. Similar to state agencies, the emphasis that these local agencies place on climate and extreme weather adaptation is influenced by their recent experience with weather-related disruptions, the projected trends in the frequency and intensity of extreme events in their area, and broader public and political perceptions about climate change. While some regions are at the forefront of the adaptation process (Nguyen, Dix et al. 2011), generally speaking adaptation at the regional and local level is considerably more limited than at the state level (Parson Brinckerhoff 2011). The adaptation barriers at the state level are frequently exacerbated at the local and regional level by the smaller size of the agencies, greater workforce development needs, and the large amount of infrastructure that they own. Moreover, the overlapping jurisdictions and the division of different responsibilities between local and regional transportation entities (the structure of which varies across the nation) create the potential for inefficient duplication of effort and confusion over the appropriate roles of each agency in the adaptation process.

A large number of different entities are involved with transportation planning and infrastructure management at the sub-state level. These entities frequently have overlapping jurisdictions and responsibilities and are very different in size and resource level. These entities include counties, cities, towns and townships, port and transit authorities as well as transportation planning organizations. Among these entities, local governments and transportation authorities own considerable infrastructure (see Table 4) but are limited in geographic extent or focused on single transportation modes, a structure that imposes limits on the ability of these agencies to undertaken broader adaptation planning.

Table 4. Selected State and Sub-state Transportation Agencies in the United States

Entities	Number of Organizations	Road Ownership[1] (% of total road length)	Bridge Ownership[1] (% of all bridges)
State DOTs	50	19%	48%
MPOs	393[2]	0%	0%
RPOs	Unknown	0%	0%
Counties	3,033[3]	44%	37%
Cities and Towns	36,011[3]	32%	12%

[1] Ownership of roads and bridges from (FHWA 2012b)

[2] Number of MPOs from (FHWA and FTA 2014)

[3] Number of counties, cities and towns from (National League of Cities 2013)

Planning organizations, including MPOs, rural planning organizations and other regional planning and economic development bodies, frequently have a relatively broad geographic reach based on system functionality and travel patterns. These jurisdictions can cross state boundaries and occupy a unique position as liaison between city, town, state and federal agencies. Additionally, many MPOs are integrated within councils of government, regional planning commissions, or other regional entities with land-use planning, economic development, and disaster recovery responsibilities, and this integration can be beneficial for adaptation planning. Consequently, MPOs offer some advantages as a sub-state locus of adaptation planning even though they do not own transportation infrastructure. The FHWA has sought to engage MPOs in the adaptation process through its climate adaptation pilot projects (Nguyen, Dix et al. 2011, SSFM International 2011) and by sponsoring a series of webinars on climate change and energy planning presented by AMPO (Parsons Brinckerhoff 2011). In 2008, AMPO convened a conference on climate change that included some discussion of adaptation measures (Resource Systems Group 2008). Several multi-county partnerships, such as the Southeast Florida Regional Climate Change Compact (now participating in the second round of the FHWA adaptation pilot projects), and individual MPOs are undertaking climate assessments that include adaptation components (McGahan and Wolfe 2012). In addition, the California DOT has issued a guide on how to incorporate adaptation in regional transportation plans (Cambridge Systematics 2013).

The size and resources of transportation planning organizations vary widely, however. Urbanized areas with a population larger than 50,000 people are required to designate an MPO to conduct transportation planning and as of 2010, there were more than 390 MPOs in the United States (FHWA and FTA 2014). These agencies covered urbanized areas ranging in size from 34 to more than 38,000 square miles and populations from 21,000 to 18 million people. MPO jurisdictions often include smaller cities, towns and surrounding rural areas as well as the urbanized area (Peckett, Daddio et al. 2014). Nonetheless, close to 80 million Americans live outside of the jurisdiction of an MPO (FHWA and FTA 2014). In many of these rural areas and smaller communities, planning functions are conducted by other regional agencies, but the degree to which these organizations conduct transportation planning is highly variable. MAP-21 provided for the designation of Regional Transportation Planning Organizations (RTPOs) but unlike MPOs, RTPOs are not required by the federal government. Currently, 32 states have adopted the RTPO model (NADO n.d.). Note, as well, that the level of resources for planning vary widely between large and small MPOs as well as these different rural agencies. Planning agencies in some cases are leaders in adaptation but in other cases lack the resources to tackle this complex topic.

Given the different capacities of agencies involved in local and regional transportation issues and the overlap of responsibilities with adaptation implications, no single local or regional agency is well-positioned to conduct all of the steps in the adaptation planning process individually (Figure 2). Instead engaging different agencies in different steps of the adaptation process is likely to maximize the overall effectiveness of adaptation planning and avoid inefficient replication of effort. It is possible that the exact role of these agencies will vary from area to area depending on the resources and capacity of local agencies, and that the state agency will have to play a larger role in poorer and more rural areas outside the jurisdiction of transportation planning organizations. In addition, a recent GCC report of community case studies makes a strong case for a significant role for citizens and non-governmental organizations in the process of planning for adaptation in the transportation system (Goldstein and Howard 2015), and additional work is need to understand the appropriate role of these organizations. The respective roles of state, regional and local agencies in each of the five steps of the adaptation framework are shown in Table 5 and discussed in greater detail in the text that follows.

The asset inventory step is logically the responsibility of the agency that owns the infrastructure. Agency personnel are frequently in contact with their own assets and some degree of condition monitoring is inherent in agencies' maintenance responsibilities. As at the state level, resource constraints were identified as the largest challenge to asset inventory and smaller agencies may have more staffing challenges and less sophisticated database management capabilities. Since asset inventory ultimately feeds the vulnerability and criticality assessments, asset inventories across levels and agencies need to be maintained in a way that allows for easy integration of these databases. This means that the state will have to take a leadership role in developing standard methods for recording asset inventory data. These standardizations may need to be done across state lines given that metropolitan areas, travel patterns and supply chains cross state boundaries suggesting a potential national role in standard development.

Detailed climate threat assessment requires considerable technical expertise as well as decisions about what climate change scenarios ought to be considered. Developing the technical expertise to conduct climate assessment at multiple levels would be duplicative and is beyond the typical scope of a local transportation agency. Moreover, the determination of what emissions scenarios ought to be considered is a social decision, reflecting the degree of risk tolerance of the society at large. Both of these factors suggest that climate threat assessment should be conducted at the state level. In many cases, the most relevant climate threats may vary from one part of the state to another (e.g. differing threats for coastal versus inland regions or mountainous versus non-mountainous regions), in which case threat assessment will need to be regionally specific. For example, determining the threat of riverine flooding due to increased precipitation intensity might include hydrological modeling, which is best undertaken at the level of watersheds. The appropriate scale for regional assessment should be determined in consultation with climate and other natural scientists. Once the climate threats have been assessed, this information needs to be passed on to local and regional agencies for planning and infrastructure design purposes.

Table 5. Adaptation Planning Role for Local Infrastructure

Component	Primary Responsibility	Notes
Inventory and Monitor Assets	Local/infrastructure owning agency	State agencies will need to provide technical support and guidance to ensure inventory asset databases maintained by local agencies can be integrated with one another.
Assess Climate Threats	State	For large states or topographically diverse states, climate threats can vary at the sub-state level and threat assessment will need to be regionally specific. Unified assessment of climate threats will reduce replicated efforts and ensure that consistent climate scenarios are used by all agencies.
Evaluate Vulnerability	Local/infrastructure owning agency	Varies based on type of threat and condition of infrastructure
Rate Asset Criticality	State or MPO/RPO	The criticality of specific infrastructure depends on network characteristics and is fundamentally cross jurisdictional and cross modal. The exact scale of analysis and appropriate boundaries, especially for non-metropolitan areas, are not yet clear.
Select and Execute Adaptation Actions	Infrastructure adaptations – owning agency Procedural adaptations – all agencies.	Owning agencies will undertake infrastructure adaptation using guidance developed at the state or national level.

The vulnerability assessment for specific infrastructure can be conducted by the agency that owns that infrastructure. The vulnerability of a specific asset to a given threat is a function of the likelihood of the threat being realized as well as the likelihood and degree that the threat will disrupt or damage the asset. For some combinations of infrastructure and climate threats, disruption is certain and, in these cases, the infrastructure vulnerability can be determined directly from the output of the climate threats assessment phase. For example, in the case of sea level rise, modeling outputs will directly reveal which roadways will be inundated for a given sea level rise scenario and all inundated roadways will be disrupted. In this case, completing the climate threat assessment directly reveals vulnerability. However, in many cases, the likelihood of disruption is related to the condition and design of the infrastructure and other local factors. For example, the likelihood that a culvert will fail during an intense precipitation event may depend on the condition of the culvert as well as the amount of upstream debris. In these cases, determining the likelihood of disruption will require additional analysis by local agencies and, once again, the staffing and resource levels required to conduct extensive vulnerability analysis is likely to be challenging. Although the vulnerability of infrastructure can be conducted town by town at the local level, it is essential to recognize that the vulnerability of all infrastructure in a given region needs to have been accurately assessed for any one agency to accurately evaluate criticality, because criticality is dependent on the vulnerability of alternative routes (across modes) regardless of asset ownership.

The criticality assessment phase may be especially prone to duplication of effort and error since asset criticality should ideally be evaluated with a complete, multi-modal representation of the full regional transportation network. This means that criticality assessment is dependent on inventory and vulnerability inputs from agencies at all levels and crosses ownership and jurisdictional boundaries. For example, adjacent bridges provide redundancy for each other and reduce the criticality of either bridge individually even if one is owned by the state and one owned by a town. As discussed previously, however, the appropriate temporal and spatial scales for conducting criticality assessment are not yet clear. The appropriate spatial scale almost certainly exceeds the size of individual cities and towns since important destinations are often outside of these boundaries. The temporal scale of criticality assessment may be threat specific, as access to some destinations are critical on the scale of hours (e.g. hospitals) and others on the scale of days or longer (e.g. grocery stores). Moreover, the appropriate scales may vary between large and small communities due to different expectations about the frequency of access to important destinations. Depending on the size of the state and planning organization, this analysis might be conducted by the state or by the MPO/RPO but it should not be limited based on infrastructure ownership. Criticality of surrounding rural areas might best be incorporated into metropolitan analysis since access to services and goods in proximate metropolitan areas is frequently important to the rural areas. Criticality assessment is a large challenge for adaptation planning for agencies of all types. Because criticality assessment requires further the methodological development, the most effective means of implementation are yet to be established.

The execution of adaptation action includes both changes to infrastructure and adaptations to agency processes. The agency that owns the infrastructure will execute the infrastructure adaptation. Guidance for infrastructure adaptation, such as appropriate culvert sizing to manage increased precipitation or pavement specifications to withstand higher temperatures, must be appropriate to the regional climate threats and is most appropriately developed at the state or national level. When infrastructure adaptations involve significant costs, the state will likely bear some portion of these costs, but prioritization will include overall importance to the regional network regardless of asset ownership. Procedural adaptations include improving inter-agency collaboration and disaster preparedness, incorporating risk in planning procedures and adjusting monitoring/maintenance schedules. Adaptations that include local land use change may be the most controversial to implement. Since many procedural adaptations have a relatively low cost, can be implemented even when the magnitude of threats is uncertain, and provide general operational benefits, all agencies may be expected to implement procedural adaptations.

Conclusions

Climate adaptation methods are advancing rapidly and both state DOTs and local transportation agencies are devoting increasing resources to adaption efforts. Nonetheless, these agencies face many barriers in implementing comprehensive climate adaptation programs. Overcoming these barriers will require a combination of additional resources, workforce development, improved cooperation, external policy decisions, and additional methodological advancements. A common, straightforward language and framework are needed to advance debate and cooperation amongst diverse partners for adaptation planning for the highway transportation system. The five-step common framework presented here uses language present in prior frameworks and reduces them to their most essential components. This approach is useful for identifying barriers to implementation and for facilitating opportunities for interregional and interagency cooperation.

Climate threats are well-understood in general terms but the magnitude of these threats is uncertain, particularly at the local scale. Without good climate forecasts, and corresponding design standards that reflect publicly accepted risk and cost benefit ratios, the extent of the infrastructure adaptation that is required to counter these threats cannot be accurately determined. Vulnerability assessment is hindered by uncertainty about climate threats and a need for better modeling tools. Methods for criticality assessment largely remain non-comprehensive or subjective, inhibiting project prioritization. Methodological research to advance criticality models, including refinements to the spatial and temporal frame of analysis as well as technical algorithms, are needed to support practitioners. Finally, all agencies face financial constraints and workforce development needs that severely limit the resources available for adaptation.

Of the five steps in our framework, our research indicates most state agencies and some local agencies have the clear expertise needed to accomplish one component (asset inventory), although they may require additional resources to complete this in a comprehensive manner. Transportation agencies also need better data on climate threats in order to adequately assess vulnerability. National and regional leadership is needed to establish greater local consensus about the appropriate emissions scenarios to use in adaptation planning. DOTs have the expertise to take both process and infrastructure adaptation actions but, again, the data, tools and resources to implement these actions are limited. Moreover, it is unclear if the infrastructure adaptation actions will be appropriately prioritized because methods to assess criticality are not well-developed. This lack of a national consensus on measurement of criticality opens the door to political and non-systematic prioritization that may be undesirable.

Given the significant infrastructure owned by local agencies, both local and regional agencies have an important role to play in the adaptation process. Unfortunately, the degree to which local agencies are currently able to engage in adaptation efforts varies widely. It is crucial to find ways to promote collaboration between these agencies and state DOTs, because collaboration reduces wasteful duplication of efforts and the technical burdens faced by smaller agencies. Moreover, we suggest that the criticality of any asset cannot be accurately assessed without knowledge of the entire regional system, regardless of ownership, and the vulnerability of the all constituent assets. A reasonable delineation of responsibilities between agencies in a partnership that minimizes duplication of effort has been outlined for the adaptation steps in this paper. Another way to improve local and regional agency efforts in adaptation planning is to increase peer-to-peer knowledge transfer. This can be further supported by helping regions and municipalities understand who is facing similar climate threats. While cities and regions often look to their immediate neighbors as examples, this many not always be the most beneficial method. The threats that an area faces are influenced by a number of geographic and topological factors that vary at the sub-state level. Developing a typology of climate threats would enable agencies to delineate the set of regions/localities that they considered peers. Climate adaptation planning is a complex, challenging endeavor and must address threats that vary considerably by region. Together, agencies and organizations have clearly established the core components of adaptation planning. The highway transportation community is increasingly active and engaged in the adaptation arena. Further advancement of a clear uniform language and appropriate tools for adaptation planning is important and will promote the transfer of knowledge from the agencies that are leading in this endeavor to other state DOTs and local agencies that are just starting their adaptation processes.

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