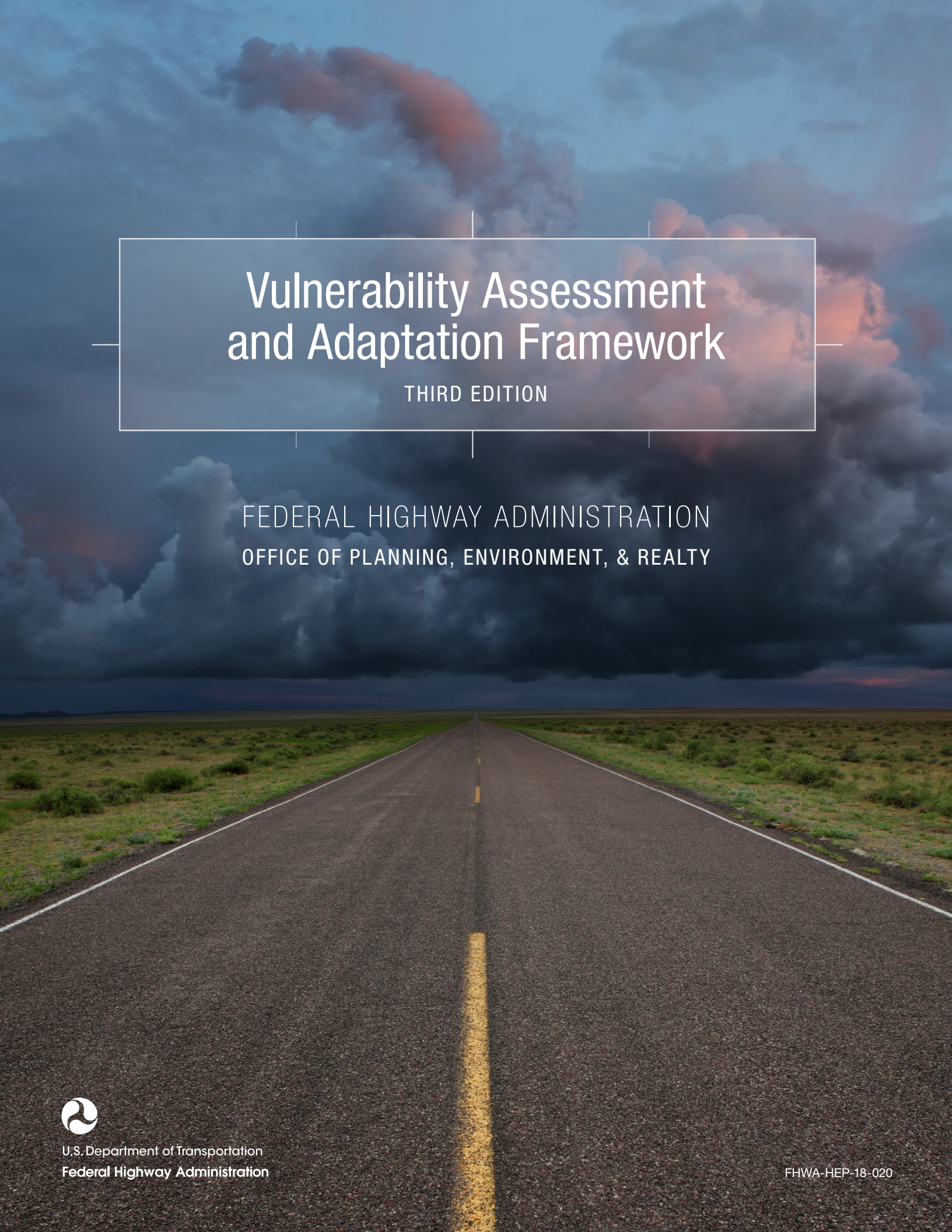

Vulnerability Assessment and Adaptation Framework

THIRD EDITION

FEDERAL HIGHWAY ADMINISTRATION

OFFICE OF PLANNING, ENVIRONMENT, & REALTY

U.S. Department of Transportation
Federal Highway Administration

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The Federal Highway Administration's (FHWA's) Vulnerability Assessment and Adaptation Framework (the Framework), third edition, is a manual to help transportation agencies and their partners assess the vulnerability of transportation infrastructure and systems to extreme weather and climate effects. It also can help agencies integrate climate adaptation considerations into transportation decisionmaking. The Framework provides an in-depth and structured process for conducting a vulnerability assessment. The Framework describes the primary steps involved in conducting a vulnerability assessment. For each step the Framework features examples from assessments conducted nationwide between 2010 and 2017 and includes links to related resources that practitioners can access for additional information. The information presented in the Framework is geared toward State departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, maintaining, or operating transportation infrastructure.

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Executive Summary

The Federal Highway Administration's (FHWA's) Vulnerability Assessment and Adaptation Framework (the Framework), third edition, is a manual to help transportation agencies and their partners assess the vulnerability of transportation infrastructure and systems to extreme weather and climate effects. It also can help agencies integrate climate adaptation considerations into transportation decisionmaking. The Framework provides an in-depth and structured process for conducting a vulnerability assessment. The information presented in the Framework is geared toward State departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, maintaining, or operating transportation infrastructure.

The Framework describes the primary steps involved in conducting a vulnerability assessment. For each step, the Framework features examples from assessments conducted nationwide between 2010 and 2017 and includes links to related resources that practitioners can access for additional information.

The steps to conduct a vulnerability assessment are:

1. Articulate objectives and define study scope. The first steps to doing a vulnerability assessment are to set objectives and determine the scope of the assessment. Establishing a clear study focus helps to bound a vulnerability assessment, minimizing extraneous data collection and analysis activities. In most cases, time and resource constraints will prevent agencies from analyzing every asset in a transportation system. Similarly, not all changes in the future climate will be significant to local or regional transportation networks. The Framework provides guidance on how to delineate which assets and climate variables to examine as part of a vulnerability assessment. This includes information on the types of climate variables that may have impacts on transportation systems and on how to determine asset sensitivity to those climate variables.

2. Obtain asset data. The study objectives and scope of a vulnerability assessment determine which asset data need to be collected. Transportation agencies likely track and maintain data on the major assets, such as roadways and bridges, which are typically a primary focus of a vulnerability assessment. They may not have as much data readily available on smaller assets and support structures, such as culverts. Coordination between internal and external stakeholders, such as local governments and universities, can be a way to identify all existing data and reduce the need to collect new data or minimize the extent of data collection efforts. The Framework provides information on the types of assets and asset characteristics that may be useful to collect data on and best practices for collecting such data.

3. Obtain climate data. A variety of resources provide information on how to obtain data on projected future climate. The Framework outlines various ways agencies can obtain projections for changes in temperature, precipitation, hydrology, floodplains, sea level, and storm surge, beginning with a basic approach to obtaining climate data and then describing more detailed methods that are useful for in-depth analyses.

4. Assess vulnerability. Vulnerability in the transportation context is a function of a transportation asset's or system's sensitivity to climate effects, exposure to extreme weather and climate effects, and adaptive capacity. Exposure refers to whether an asset or system is located in an area experiencing direct effects of climate change; sensitivity refers to how the asset or system fares when exposed to a climate variable; and adaptive capacity refers to the system's ability to cope with existing climate variability or future climate impacts. In order to assess vulnerability, practitioners will use the climate and extreme weather variables they developed to identify and evaluate the exposure, sensitivity, and adaptive capacity of an asset or system to determine its vulnerability, and, typically, assign a level of risk of the climate impacts

on the asset/system. Risk is a measure that considers both the probability that an asset will experience a particular impact and the severity or consequence of the impact. The Framework outlines three approaches to assessing vulnerability. The first two approaches, stakeholder input and indicator-based desk review, are primarily used for systems level or area analyses, while the third approach, engineering-informed assessment, focuses on a specific transportation asset. The approaches each differ by the types of stakeholders involved, the forms of information required, and the formats of the final vulnerability assessment findings. The approaches are not mutually exclusive; often a vulnerability assessment includes elements of each approach. Determining which approach is best for an agency depends on the agency's goals for the vulnerability assessment and the resources available to conduct the assessment.

5. Identify, analyze, and prioritize adaptation options. After assessing vulnerabilities, an agency can identify, analyze, and prioritize adaptation options. Adaptation solutions can be natural, structural, or policy-based and can range from site-specific to regional. The Framework describes two methods that practitioners can use to evaluate adaptation options: multi-criteria analysis (MCA) and economic analysis. MCA involves comparing adaptation options across a range of qualitative and quantitative criteria. One benefit of MCA is that it allows practitioners to consider aspects that cannot easily be quantified or put into monetary terms, such as impacts to the environment or communities. An economic analysis can help agencies evaluate and prioritize adaptation options by clarifying the potential long-term costs and benefits of alternative adaptation strategies. It can measure those costs and benefits in terms that allow the options to be compared individually, as well as with current policies and practices.

6. Incorporate assessment results in decisionmaking. Integrating the results of a vulnerability assessment into existing transportation programs and processes ensures that study results are used in practice. While information developed for the vulnerability assessment should be used to satisfy the study objectives, the results may also be useful in ways not initially anticipated. The Framework outlines strategies to effectively incorporate results into transportation planning; project development and environmental review; project level design and engineering; transportation systems management, operations, and emergency management; and asset management.

7. Monitor and revisit. The understanding of climate risks evolves. Accordingly, adapting to extreme weather and climate impacts is an iterative process that requires monitoring and evaluation. Agencies should establish monitoring and evaluation processes to assess the success of adaptation strategies and other initiatives that were established based on assessment findings. As new climate science and data become available, agencies may need to reassess their vulnerabilities. The monitoring and evaluation process may identify the need to revisit the assumptions, underlying data, or approaches used in the original vulnerability assessment. The results of the monitoring and evaluation can also be used to periodically revisit and refine adaptation strategies and processes to ensure continued resilience of transportation infrastructure.

The resources mentioned throughout the Framework and its Appendices provide detailed information that agencies can refer to as they develop the scope of their assessment, collect data, assess vulnerabilities, and integrate the results into decisionmaking. Moving forward, FHWA will build off of the information in this Framework and continue to work with its partners to provide transportation agencies with resources to assess vulnerability and build their resilience to extreme weather and climate impacts.

Introduction

Extreme weather events such as flooding, severe heat, and intense storms threaten the long-term investments that Federal, State, and local governments have made in transportation infrastructure. Transportation systems are already experiencing costly climate-related impacts, leading to disruption and damaged roads, bridges, rail systems, and other transportation infrastructure. In the future, these impacts are projected to intensify in magnitude, duration, and frequency across the United States. This document provides resources and examples to support transportation agencies with assessing vulnerabilities to climate impacts and identifying ways to protect, preserve, and improve transportation assets and services.[1] Assessing and addressing vulnerabilities allows agencies to build their resilience, or the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

Congress addressed the issue of improving the condition and resilience of transportation assets in the past two transportation authorization bills. The Moving Ahead for Progress in the 21st Century Act (MAP-21, 2012) required each State to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system.[2,3] MAP-21 established the National Highway Performance Program (NHPP), which provides support for improving the condition and performance of the NHS and for the construction of new facilities on the NHS. The NHPP also provides support to ensure that investments of Federal-aid funds in highway construction are directed to support progress toward achievement of performance targets established in a State's required asset management plan. To conserve Federal resources and protect public safety, MAP–21 also mandated periodic evaluations to determine if reasonable alternatives exist to roads, highways, or bridges that repeatedly require repair and reconstruction. MAP-21 also allowed the Federal Highway Administration (FHWA) to provide Federal aid funds for construction, replacement, rehabilitation, preservation, and protection (including protection against extreme events) of bridges and tunnels on the NHS[4] and on public roads of all functional classifications.[5]

The Fixing America's Surface Transportation (FAST, 2015) Act continued the NHPP and expanded funding eligibility specifically to projects that reduce the risk of failure of critical NHS infrastructure (i.e., a facility whose incapacity or failure would have a debilitating impact in certain specified areas).[6,7] In addition, the FAST Act requires transportation agencies to take resilience into consideration during transportation planning processes. The updated metropolitan and statewide transportation planning regulations include a requirement that the metropolitan transportation plan assess capital investment and other strategies that reduce the vulnerability of the existing transportation infrastructure to natural disasters.[8]

In 2014, FHWA established a policy on resilience, FHWA Order 5520, Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events. This order states that it is FHWA policy to strive to identify the risks of climate change and extreme weather events to current and planned transportation systems, and to integrate consideration of these risks into its planning, operations, policies, and programs in

[1] Throughout the Framework, the term "asset" refers to both physical transportation infrastructure such as roads, rails, and bridges as well as support facilities, vehicles, intelligent transportation systems, and ecosystem-related facilities [or "features"].

[2] 23 U.S.C. 119(e)(1), MAP-21 § 1106)

[3] "Asset Management." U.S. Department of Transportation/Federal Highway Administration. February 25, 2016. Accessed June 23, 2017. https://www.fhwa.dot.gov/asset/plans.cfm.

[4] 23 U.S.C. § 119(d)(2)(B) and (C)

[5] 23 U.S.C. § 133(b)(2)

[6] 23 U.S.C. 119(j)(3)

[7] "National Highway Performance Program (NHPP)." U.S. Department of Transportation/Federal Highway Administration. February 26, 2016. Accessed June 23, 2017. https://www.fhwa.dot.gov/fastact/factsheets/nhppfs.cfm.

[8] 23 CFR 450.324(g)(7)

order to promote preparedness and resilience.

FHWA's *Vulnerability Assessment and Adaptation Framework, 3rd Edition,* (hereafter, "the Framework") is a collection of resources to assist transportation agencies and their partners with conducting vulnerability assessments and integrating climate adaptation considerations into transportation decisionmaking to help them meet the requirements of these laws and mandates. The updated Framework provides more examples from assessments conducted nationwide and a more structured process for conducting vulnerability assessments. This document identifies key considerations, components, and resources to help agencies design and implement vulnerability assessments and climate change adaptation strategies.

The information and resources presented in this Framework are geared toward State departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, maintaining, or operating transportation infrastructure. The Framework provides information on a range of applications, from small qualitative studies to complex, quantitative-driven analyses, and from the State or regional (metropolitan) systems level analysis down to corridor- or project-specific analyses. Several recent programs and studies inform the Framework, including FHWA's climate change resilience pilot programs (five pilot projects conducted from 2010–2011, and 19 pilot projects conducted from 2013–2015), and various adaptation-related studies conducted by FHWA and its USDOT partners.

This Framework consists of the following sections:

Section 1: Articulating Objectives and Defining Study Scope

Section 2: Obtaining Asset Data for the Vulnerability Assessment

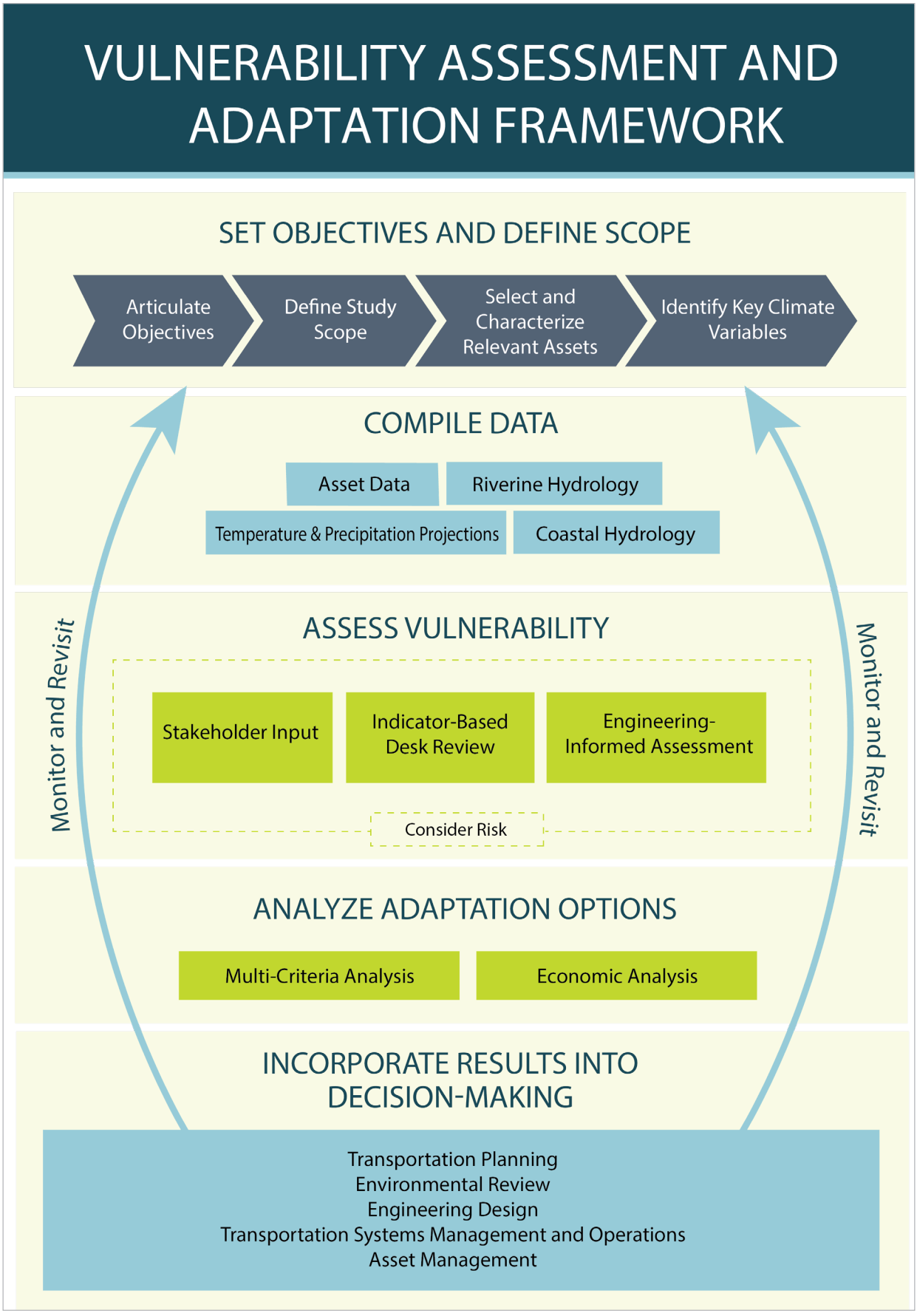
Section 3: Obtaining Climate Data for the Vulnerability Assessment

Section 4: Assessing Vulnerability

Section 5: Identifying, Analyzing, and Prioritizing Adaptation Options

Section 6: Incorporating Assessment Results in Decisionmaking

Each section of the Framework features examples, many of which are FHWA pilot projects, that showcase how different agencies have undertaken a vulnerability assessment. Each section also includes references to related resources that practitioners can access for additional information.


VULNERABILITY ASSESSMENT AND ADAPTATION FRAMEWORK
SET OBJECTIVES AND DEFINE SCOPE
Articulate Objectives
Define Study Scope
Select and Characterize Relevant Assets
Identify Key Climate Variables
COMPILE DATA
Asset Data
Riverine Hydrology
Temperature & Precipitation Projections
Coastal Hydrology
ASSESS VULNERABILITY
Monitor and Revisit
Stakeholder Input
Indicator-Based Desk Review
Engineering-Informed Assessment
Consider Risk
Monitor and Revisit
ANALYZE ADAPTATION OPTIONS
Multi-Criteria Analysis
Economic Analysis
INCORPORATE RESULTS INTO DECISION-MAKING
Transportation Planning
Environmental Review
Engineering Design
Transportation Systems Management and Operations
Asset Management

1 Articulating Objectives and Defining Study Scope

The first steps in a vulnerability assessment are to set objectives, which define the specific focus of the assessment, and to determine the scope of the assessment. Establishing a clear study focus helps to provide boundaries for a vulnerability assessment, minimizing extraneous data collection and analysis activities. In most cases, time and resource constraints will prevent agencies from analyzing every asset in a transportation system. Similarly, not all changes in the future climate will be significant to local or regional transportation networks. An important part of scoping the assessment, therefore, is delineating which assets and climate variables to examine in order to meet the objectives of the study.

Setting a study's objectives is typically the first step in the assessment process; however, agencies may find it useful to simultaneously characterize relevant assets and identify climate variables.

ARTICULATING OBJECTIVES

Articulating the objectives of the vulnerability assessment early in the process helps define the level of detail, types of data and tools, and range of expertise and skills needed to carry out the assessment. Consider the following questions when developing assessment objectives:

- What type of agency decisions or actions should the assessment inform?
- What efforts has the agency previously conducted related to assessing vulnerabilities?
- What relevant climate adaptation assessments have others done (e.g., studies by other agencies and/or sectors for the geographic area, or studies for the transportation sector from similar locations)?
- What is motivating the need for the assessment?
- Who will use the information provided by the assessment?
- What results or products are needed and how will they be used?
- What level of detail (spatial, geographic, and temporal) is required?

Vulnerability assessments can range from network-based planning studies to detailed asset-specific analyses. Example objectives include:

- Understand the vulnerability of an agency's overall transportation system to climate change.
- Assess the vulnerability of tunnels to sea level rise and extreme storm events.
- Identify locations where highways are vulnerable to hazards caused by extreme events, such as high temperatures or heavy rainfall.
- Evaluate future change in exposure to critical streamflow levels and assess changes in bridge vulnerability.
- Develop detailed, action-oriented adaptation options for vulnerable transportation assets.
- Plan for the siting of new projects and the ability to operate these new assets.
- Identify cost-effective risk management strategies for incorporation into short-term and long-range transportation planning.
- Implement operational or design changes to mitigate climate vulnerabilities.

Looking at previous climate adaptation assessments for the region and/or sector when developing assessment objectives can help practitioners identify available data, ensure that their work does not duplicate previous efforts, and learn from the experiences of other agencies that have done similar studies.

Examples: Articulating Objectives

- The Dallas-Fort Worth region had not previously conducted an assessment of climate change impacts on transportation. As such, the objective of the **North Central Texas Council of Governments' (NCTCOG's) vulnerability assessment** was to bring together stakeholders and conduct a broad assessment of the vulnerability of the region's transportation system to the types of climate change impacts expected for the region.
- The Metropolitan Transportation Commission (MTC), the MPO for the San Francisco Bay area, had been participating for several years in a regional climate adaptation effort called "Adapting to Rising Tides," and had completed an **earlier pilot effort with FHWA** that identified specific areas within Alameda County that are susceptible to sea level rise and storm events. The objective for **MTC's second pilot** with FHWA was to refine its understanding of vulnerability and risk and to develop potential adaptation solutions for important transportation assets in three areas within Alameda County that the earlier study identified as particularly vulnerable to sea level rise and storm surge.
- The **Iowa Department of Transportation** (Iowa DOT), which has experienced major river flooding that closed interstate highways and bridges, conducted a vulnerability assessment to consider implications of projected changes in precipitation on six bridges in two watersheds. Iowa DOT's objective was to assess the sensitivity of the bridges to simulated streamflow using an integrated asset database and monitoring software that warns travelers of potential disruptions from flooding. Iowa DOT ultimately wants to develop an interactive and proactive planning process for the maintenance, repair, and replacement of Iowa's primary highway structures that are vulnerable to flood inundation during severe rainfall events.
- **The Massachusetts Department of Transportation** (MassDOT) wanted to determine how the Central Artery/Tunnel system (CA/T) in Boston, which is a critical component of the regional transportation network, could be adapted to handle sea level rise and flooding from future extreme weather events. Though previous studies had been conducted on the potential risks of extreme weather events and rising temperatures in the Boston metropolitan area, MassDOT wanted a finer-scale analysis to better understand the magnitude and extent of flooding for the CA/T.

Resources: Articulating Objectives

Video: Articulating the Objectives of a Vulnerability Assessment, FHWA, 2015. In this short video, Sandy Salisbury, Roadside and Site Development Manager for the Washington State Department of Transportation (WSDOT), walks through the process WSDOT followed for its vulnerability assessment pilot project. Sandy describes the importance of setting objectives, the process that WSDOT used to identify the objectives of its vulnerability assessment, and the need to revisit and refine objectives over time.

Formulating Vulnerability Assessment Teams

Deciding who will be involved in the vulnerability assessment affects how it is conducted, the outcomes, and how the information will be used. A cross-disciplinary team is often needed to effectively address the range of issues included in the assessment. In addition, some transportation agencies choose to form an interdisciplinary technical advisory committee with individuals either internal or external to the agency to provide input to the team conducting the vulnerability assessment at different stages of the process. Engaging agency leadership is also paramount as a champion is often needed to ensure the results of the study are used in future decisionmaking.

Each of the stakeholders listed below may have expertise and knowledge to contribute to a vulnerability assessment. Having clearly defined objectives before establishing the vulnerability assessment team will help practitioners determine the team's composition and the level of involvement needed from each team member. Not all stakeholders included in this list will be actively engaged in the assessment, but they can be called upon at certain milestones to provide relevant guidance and expertise.

- **Transportation planners** are responsible for long-range planning of the transportation system and regularly use scenario planning and other tools for planning long-term investments and policies in the face of uncertain futures.
- **Asset managers** are familiar with the conditions of transportation infrastructure and may have relevant datasets.
- **District-level staff and maintenance personnel** have on-the-ground familiarity with and institutional knowledge of how current and past weather events affect transportation assets, and what is needed to maintain and operate the system.
- **Emergency responders** (e.g., fire and police departments and emergency response staff within DOTs) provide rapid-response to natural disasters and are familiar with evacuation routes and other operational needs during severe weather events.
- **Engineers** (e.g., structural, hydraulic, coastal, or other relevant disciplines) can provide input into the sensitivity of infrastructure to climate impacts and propose ideas for and anticipated costs of adaptation solutions.
- **Transportation systems management and operation staff** have knowledge about how climate and extreme weather can impact traffic congestion and traveler safety, and what is needed to minimize service disruption, delay, and crashes in such situations.
- **Geographic Information System (GIS) specialists** can spatially analyze and display transportation assets and vulnerability information.
- **State level environmental staff** (e.g., DOT environmental staff and State environmental agency staff) can provide insight into how projected changes might impact ecosystems and the benefits ecosystems provide. Environmental or natural resource agencies may have access to local datasets or knowledge of climate change research conducted by other organizations that can be useful for the transportation study.
- **Governmental and university climate science research centers** can provide targeted, geographically-focused climate projections.
- **State climatologists** can provide information and insight on historical climate data and trends and, in some cases, future projections.
- **Municipal government staff** can provide information on assets within their jurisdiction, and have staff with expertise in a variety of areas relevant to the vulnerability assessment, such as emergency management and roadway maintenance.

DEFINING STUDY SCOPE

A vulnerability assessment examines how climate stressors (e.g., increased annual precipitation) may directly or indirectly affect important transportation assets (e.g., bridges). To define the study's scope: 1) select and characterize important transportation assets to study and 2) identify key climate variables[9] that could impact those assets.

In determining a vulnerability assessment's scope, it is critical to include a variety of stakeholders who will be participating in the assessment, including engineers, operations and maintenance staff, climate scientists, and others who are familiar with the available asset and climate data for the region.

The following section provides information on how to select and characterize assets to include in the assessment, followed by a section on how to identify key climate stressors to study.

SELECTING AND CHARACTERIZING RELEVANT ASSETS

Identifying relevant assets and determining which characteristics of the assets to examine will focus the scope of the assessment, making it more manageable while providing opportunities for in-depth investigation of the selected assets.

A wide range of asset types and system services could be considered in a vulnerability assessment, depending on an agency's objectives. Transportation infrastructure such as roads, rails, and bridges will be a major focus for most agencies, but assets can

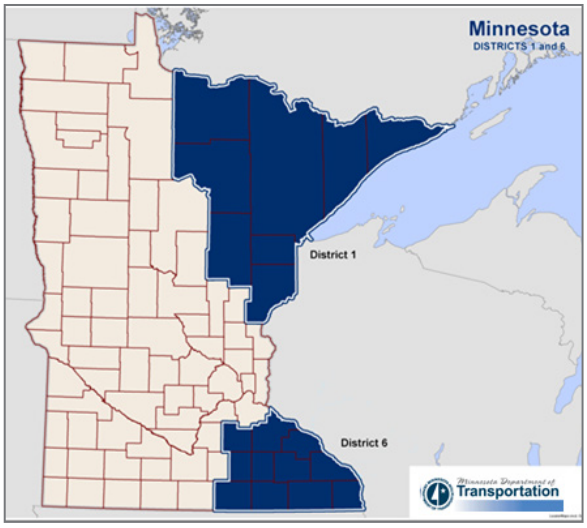
[9] Climate variables may reach thresholds that cause harm to the transportation system. In such situations, climate variables describe climate stressors, hazards, or threats to the system. An example of a climate variable may be daily precipitation and the associated threshold of harm may be any day receiving at least nine inches of rainfall.

also include support facilities, vehicles, intelligent transportation systems, and ecosystem-related assets.[10]

There are a variety of factors that an agency can use to select which assets to include, such as:

- **Jurisdictional.** Agencies may choose to limit the assessment to assets that are within their control (e.g., State-owned facilities for a State DOT analysis). Though less comprehensive, a vulnerability assessment restricted to assets under the agency's jurisdiction can more directly inform future actions by the agency. The Arizona DOT (ADOT) selected an interstate corridor for its pilot study (see Figure 2).
- **Geographic.** Specific areas may be more vulnerable to some climate variables. For instance, low-lying areas are more vulnerable to sea level rise or river overflows. An agency might focus on these areas to limit the analysis to the assets most likely to be affected by flooding events (see Figure 1).
- **Representative.** An agency interested in understanding the range of climate variables that might affect its system could select a small number of assets that represent the different types of infrastructure and assets found within its transportation system.
- **Repeatedly impacted.** Assets that are subject to frequent flooding and debris problems or assets that have been repeatedly repaired or replaced due to extreme weather events may be most vulnerable to additional stressors introduced by climate change.
- **Stage of life.** Agencies may choose to focus on assets that are scheduled for rehabilitation and/or replacement in the near future, or on infrastructure that does not meet current design standards. For assets that have a long design life, such as bridges, transportation agencies do not frequently have opportunities to redesign the asset, so incorporating vulnerability and resilience into the rehabilitation or replacement is especially important. In addition, it may be more feasible and less costly to incorporate adaptation strategies into an asset rehabilitation or replacement project, rather than as a standalone project.
- **Most critical.** Agencies may focus on the most critical elements of the transportation system, identified using quantitative or qualitative criteria. Such a method provides a structured way to focus on the assets that are most important for the transportation system to function. This method may help conserve resources by limiting the analysis while providing focus early in the study. See the next section for more information on how to conduct a criticality assessment.
- **Existing and planned assets.** The vulnerability assessment's objectives and audience should help determine whether it is useful for a vulnerability assessment to include planned assets, in addition to existing ones. For example, if the objective of the assessment is to help an MPO consider climate change impacts in its long-range planning efforts, then it would be useful to include the future, planned assets that are in the long-range transportation plan in the list of assets to be analyzed.

Figure 1. Minnesota DOT Vulnerability Assessment Study Area Map



For its pilot, the Minnesota DOT selected two districts that have experienced particularly severe flooding in recent years: District 1 in northeast Minnesota and District 6 in the southeastern portion of the State (Source: MnDOT).

Data availability may be a factor that limits which assets are included in a vulnerability assessment. For example, an assessment often needs a variety of asset data, but only some of it may be readily available from agency databases. In some cases, the asset data needed for the assessment may be spread across multiple databases, stored in varying formats, or difficult to access. Particularly for agencies conducting quantitative assessments, it may take significant effort to gather the necessary information and convert it into a usable format.

Types of asset data that can be useful for vulnerability assessments include (but are not limited to):

- Age of asset
- Design life and stage of life
- Geographic location (including whether the asset is located in a floodplain)
- Elevation information[11]
- Current and historical performance and condition
- Level of use (e.g., traffic counts, forecasted demand)
- Replacement cost
- Maintenance schedule and costs
- Evacuation routes
- Emergency management/response costs
- Occurrence/location of maintenance events
- Structural design (as-built plans if available)
- Materials used in construction and repair
- Pavement quality (roughness/smoothness)
- Degree of redundancy in the system

[10] Ecosystem-related assets could be included in an analysis of how climate change might affect environmental commitments or the ecosystem services on which the agency or others rely.
[11] For roadways it would be helpful to have elevation data for centerline or each lane if available.

Evaluating Asset Criticality

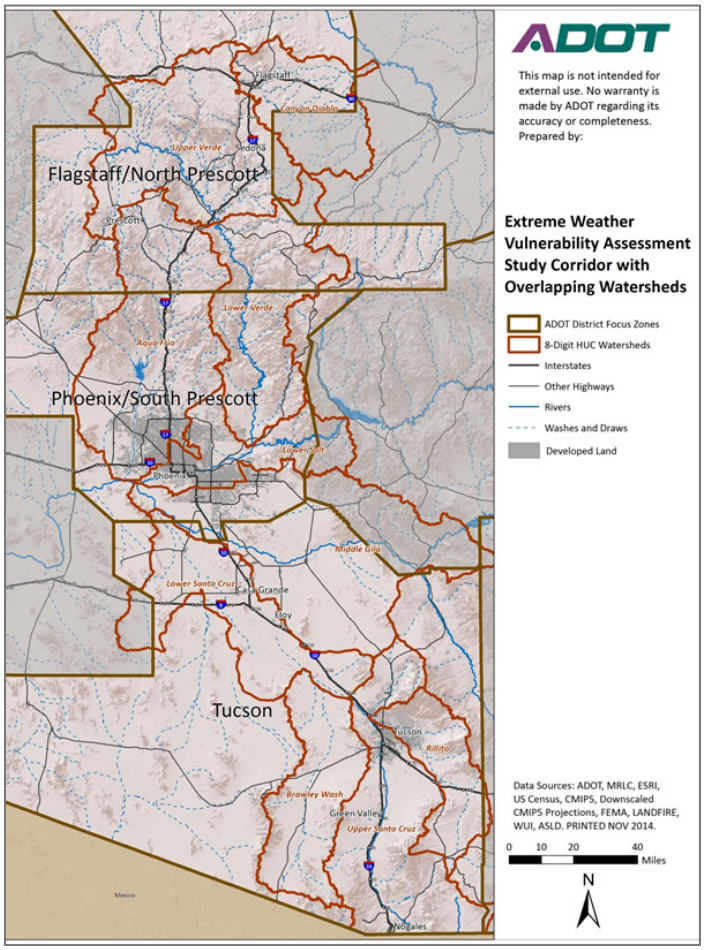
Agencies that need a more structured approach to identify which assets to focus on in their vulnerability assessment may find it useful to conduct a criticality assessment. However, conducting a criticality assessment can be resource and data intensive, and in many cases an agency will be able to decide which assets to include in its study without this step.

Asset Data May Be Lacking. The type of information that is helpful for vulnerability assessments is often not readily available at the asset level as it has not historically been a regular part of asset data collection. Incorporating additional data—such as culvert slope, as-built information, and flood history—as part of asset management processes can improve the quality of vulnerability assessments in the future.

Examples: Selecting and Characterizing Relevant Assets

- In its **first pilot project,** WSDOT conducted a high-level statewide assessment to identify areas of the State that are considered vulnerable. WSDOT focused on transportation infrastructure that it owns, including roads, rails, terminals, and airports. The assessment focused on existing assets and assets that will be built as outlined in funded projects (either permitted or in final design), but did not include proposed projects in transportation plans. In its **second pilot,** the agency conducted a more detailed analysis of assets in the Skagit River Basin (one of the areas identified as highly vulnerable to flooding in the earlier study). WSDOT then developed adaptation strategies for a set of 11 vulnerable road segments in the Skagit River Basin.
- **Connecticut DOT** analyzed the hydrologic and hydraulic performance of agency bridge and culvert structures under inland flooding conditions. The agency chose to focus on facilities and assets that 1) had not been comprehensively studied before, and 2) were located in an inland, northwest corner of the State with limited detour and accessibility options in the event of a structure failure. The project team used the State's bridge inventory to identify 60 culvert/bridge structures that met a set of criteria related to asset condition and criticality.
- **Arizona DOT** (ADOT) focused on a 300-mile Interstate corridor (I-19, I-10, and I-17) that connects some of the State's largest cities (see Figure 2). The study area was chosen because it includes a variety of urban areas, landscapes, biotic communities, and climate zones, and hosts a range of weather conditions applicable to much of Arizona.
- **Minnesota DOT** (MnDOT) focused on two districts that have experienced severe flooding in recent years. MnDOT conducted a system-wide flash flood vulnerability assessment for the entire trunk highway network in both districts, including bridges, culverts, pipes, and roads paralleling streams susceptible to flooding.
- Four counties in **Southeast Florida,** led by the Broward MPO, focused on "regionally significant"[12] road and passenger rail infrastructure in the four-county region.

Figure 2: ADOT Vulnerability Assessment Study Area Map



ADOT studied an interstate corridor with a variety of urban areas, landscapes, biotic communities, and climate zones. The entire corridor was deemed critical, so further efforts to refine the scope were not undertaken. (Source: Arizona DOT)

[12] The Southeast Florida Transportation Council, an organization that provides enhanced coordination of regional transportation planning activities, defined the system and assets for study. These included regional freeways and arterials, and the regional passenger rail line.

Criticality assessments typically combine both quantitative data and qualitative information from stakeholders to identify the most critical elements of the transportation system. An agency may start with a desk review approach that uses quantitative information from available data sources to rank assets based on a broad range of criteria that capture use and access across different transportation modes and systems. Criteria for evaluating an asset's criticality may include: average daily traffic, functional classification, goods movement levels, access to employment/educational/medical facilities, degree of redundancy, and role in emergency management. Agencies then ask local experts and stakeholders to verify based on direct observation or experience and provide input on assets identified as critical. To gather stakeholder input, project leaders may identify a group of regional stakeholders with expert knowledge of specific topics (e.g., commercial activities and public safety) and organize workshops or other events to elicit feedback on assets they believe to be critical.

Including stakeholders in the process to assess criticality can help to generate buy-in early in the process and encourage collaboration and communication among stakeholders and actors likely to implement adaptation strategies. The outcomes of the stakeholder approach depend strongly on the quality of the workshop/meeting facilitation, the composition of workshop/meeting attendees, and the participation of experts. Organizers should carefully consider these factors when designing the workshops or meetings.

Criteria for evaluating an asset's criticality may include: average daily traffic, functional classification, goods movement levels, access to employment/educational/medical facilities, degree of redundancy, and role in emergency management.

ADOT—WTS Transportation YOU South Mountain Freeway Tour. Photo © ADOT.

Examples: Determining Asset Criticality

- **The Capital Area Metropolitan Planning Organization (CAMPO)** study team convened a half-day workshop of regional stakeholders from the Texas Department of Transportation (TxDOT), two counties and four cities in the study area, CAMPO, and the Central Texas Regional Mobility Authority (CTRMA) to help identify a limited set of critical transportation assets to include in its vulnerability assessment. At the workshop, local stakeholders developed a set of advisory criteria to facilitate critical asset selection. The selected assets were chosen to meet the following criteria:
  - » Align with regional transportation planning goals;
  - » Provide significant access and connections;
  - » Reflect the region's multimodal system;
  - » Take into account the region's extreme weather vulnerabilities;
  - » Broadly represent similar assets; and
  - » Consider geographic and social diversity.

Based on available data, CAMPO selected nine critical assets from the stakeholders' list.

- **Tennessee DOT l**ooked at 12 different asset types: roads, railroads, rail yards, navigable waterways, ports, locks, bridges, airport runways, maintenance facilities, support systems, transit, and pipelines. The study team developed and applied criteria for what constitutes a critical asset, defining one as any portion of the transportation system without which there would be an immediate, direct, and substantial disruption to the transportation system at the local, regional, or national level. To "ground truth" the asset inventory, asset characteristics, and degree of criticality ("critical," "important," or "other"), the team held a series of regional stakeholder focus group meetings. Attendees included personnel from TDOT maintenance, county planning organizations, MPOs, local airport authorities, transit agencies, private consultancies, and city sustainability offices. At the workshops, the study team displayed maps of the critical assets and asked participants to verify their initial selection of critical assets.
- The **USDOT Gulf Coast Study** team developed criteria to rate the criticality of assets for each of the transportation modes included in the study (i.e. highways, transit, railroads, ports, airports, and pipelines). Asset criticality was rated according to three sets of criteria:
  - » **Socioeconomic:** To what extent do roads/assets provide linkages between modes, among populations, or to economic centers? Links to key community (schools, government facilities) and economic centers and facilities lacking redundant or parallel roads scored higher;
  - » **Use/operational:** How much are assets used to transport freight or people? The use of each link or node in the system. Highly used infrastructure (in terms of volume), intermodal connectors are viewed as more important than lesser used segments; and
  - » **Health and safety characteristics:** To what extent do assets provide connections for evacuation, disaster recovery, national defense purposes or to health facilities/hospitals?

The resulting scores were presented to local stakeholders for feedback. The local stakeholders noted that certain important assets/areas had not been captured through the assessment process, and as a result adjustments were made to the list of critical assets.

Resources for Selecting Transportation Assets

Video: Selecting Assets to Evaluate in a Vulnerability Assessment, FHWA, 2015. In this short video, Tian Feng, district architect for the San Francisco Bay Area Rapid Transit District (BART), describes how his agency selected critical assets to evaluate in its vulnerability assessment. BART has a broad range of asset types, so the agency used five criteria to screen and select assets for the study. The criteria required that the asset (1) be located within the study area; (2) be typical, repetitive, and vital to the overall system's operation; (3) be impacted by one or more of the climate change scenarios being considered; (4) be involved with capital improvement and investment; and (5) have historical data available on disruptions from weather events.

Assessing Criticality in Transportation Adaptation Planning, FHWA, 2014. This memo discusses approaches for narrowing the universe of transportation assets to focus on in a climate change vulnerability assessment by evaluating their criticality. It discusses common challenges associated with assessing criticality, options for defining criticality and identifying scope, and the process of applying criteria and ranking assets.

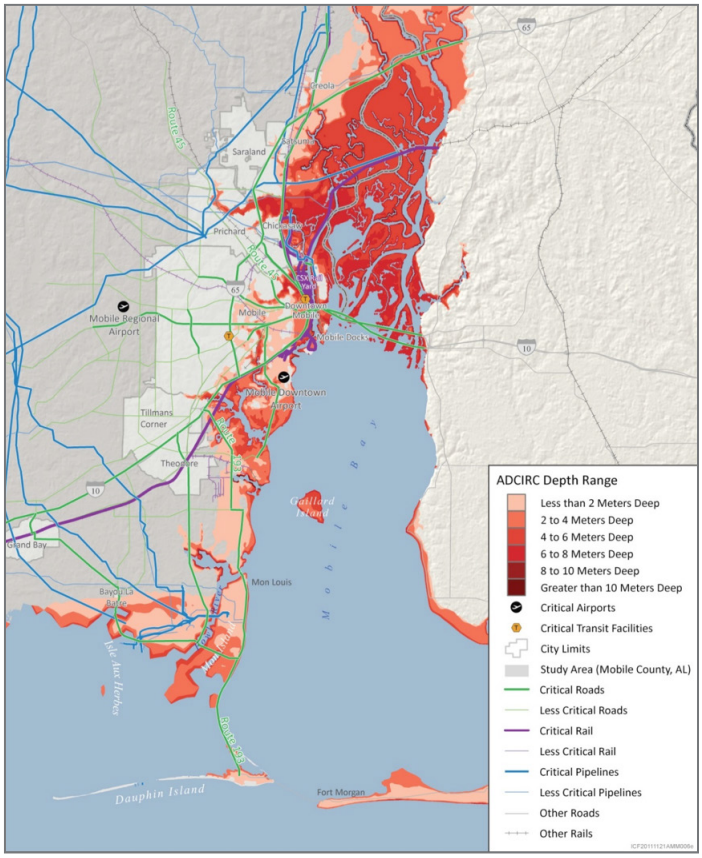
IDENTIFYING KEY CLIMATE VARIABLES TO STUDY

The next step in conducting a vulnerability assessment is to identify which climate variables to focus on. Not all future changes to the climate will have significant effects on an agency's transportation system; the climate variables that are important will vary by region.

Examples of climate variables that may have impacts on transportation systems include, but are not limited to, the following:

- **Temperature.** Temperature is projected to increase in almost every part of the country in the coming decades.[13] For the transportation sector, some stressors include increases in the number of very hot days and heat waves and changes to freeze-thaw cycles. These impacts may result in changes to the length of the construction season and higher rates of evaporation and drier soil, affecting rates of erosion and pavement degradation.

Figure 3: Modeled Storm Surge Depth for Mobile, Alabama



The USDOT used the Advanced CIRCulation (ADCIRC) model followed by the Steady State spectral WAVE (STWAVE) model to simulate storms in the study area based on historical hurricanes. This image shows the modeled storm surge depth if a storm similar to Hurricane Katrina directly hit Mobile, AL under a scenario of 2.5 foot (0.75 meter) sea level rise (using NAVD88 datum) (Source: USDOT).

Climate variable: the condition (e.g., precipitation) that affects the transportation system and will be analyzed in a vulnerability assessment.

Climate stressor (also referred to as a hazard or a threat): the magnitude(s) of the climate variable (e.g., more frequent precipitation events) that may harm the system.

- **Precipitation.** Many of the most significant future impacts on the U.S. transportation system will likely be due to the intensification of precipitation events. Over the last several years, a number of significant flood events, including Hurricane Irene (2011), Superstorm Sandy (2012), Hurricane Harvey, Irma, and Maria (2017) and flooding events in Colorado (2013), Florida (2014), South Carolina (2015), and the Midwest (December 2015), have caused substantial damage to transportation infrastructure. Climate models project continued increases in heavy precipitation events across much of the U.S.;[14] Federal agencies are studying whether or not this increase in precipitation will correlate to an increase in the types of extreme precipitation events that cause flooding interruptions and damage to roads. The cumulative effect of smaller, more frequent precipitation events can also cause increased structural vulnerability and damage to transportation infrastructure.
- **Sea Level.** Sea levels are changing along U.S. coastlines at varying rates. The 2014 U.S. National Climate Assessment projects sea level to rise by 1 to 4 feet this century, with some scenarios suggesting as much as 6.6 feet.[15] Rising sea levels present the risk of permanent or periodic inundation of coastal infrastructure as well as increased coastal erosion, possible loss of coastal vegetative buffers, rising groundwater levels, and changes in salinity. Sea level rise may also reduce navigational bridge clearances and jeopardize low-lying access roads to major port facilities.
- **Storm Surge and Waves.** Coastal storms may intensify in the future, leading to larger storm surges and wave heights. Rising sea levels pose additional risks during storms by exacerbating the impact of storm surges. When coupled with rising sea levels, storm surges will extend further inland relative to today's coastline, leading to inundation of coastal communities and their transportation assets. See Figure 3 for an example of how the USDOT mapped potential storm surge and wave heights in the Gulf Coast Phase 2 Study.
- **Permafrost Thaw.** In Alaska, much transportation infrastructure is built on permafrost foundations. Warming temperatures in the Arctic are already causing thawing in interior and southern Alaska. Continued thawing will to lead to uneven sinking of the ground, causing impacts to the design and maintenance of infrastructure.[16]

[13] "National Climate Assessment." National Climate Assessment. October 2014. Accessed June 23, 2017. http://nca2014.globalchange.gov/.

[14] ibid

[15] ibid

[16] ibid

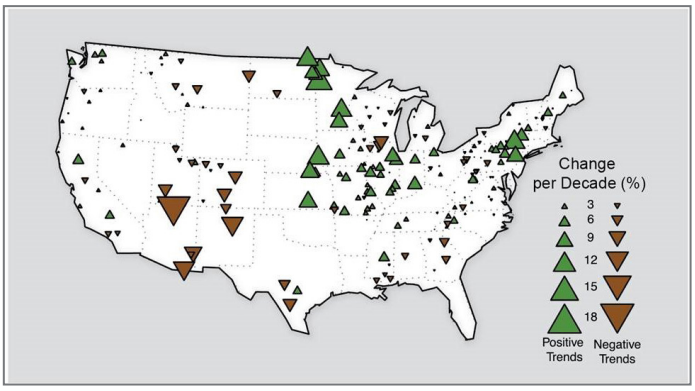
- **Streamflow.** Changes in the magnitude of peak annual river floods since the 1920s are shown in Figure 4 for watersheds that have experienced little or no land-use or water management changes. While much of the U.S. shows little or no change in flooding, some areas have experienced changes. Several recent studies support the findings that flood magnitudes have been decreasing in the Southwest and increasing in much of the Midwest and Northeast.[17,18,19] Increases in flood magnitudes and frequency can damage or destroy roads, bridges, and culverts, requiring reconstruction, resurfacing, and increased maintenance activities. Days with heavy precipitation have also increased significantly across the eastern U.S., particularly in New England.[20,21] However, this trend is not strongly related to changes in river flooding.[22] Continuing to collect empirical data on streamflow changes as greenhouse gas (GHG) concentrations change over time can provide a valuable check on global climate model-driven studies (see the Understanding Climate Projections and Uncertainty box in Chapter 4 for more information on global climate models).
- **Drought.** Prolonged periods with hot temperatures and little rainfall can result in higher rates of evaporation and drier soil, leading to higher rates of erosion and pavement degradation. Drought also increases the probability of wildfire, which can affect visibility and lead to road and airport closures. Wildfires can significantly alter the hydrologic response of a watershed to the point that modest rainstorms produce dangerous flash floods and debris flows.[23] Moreover, drought weakens vegetation and makes it more susceptible to pests, whic h can also lead to issues with debris.

Selecting Climate Variables to Study

To assess vulnerability, practitioners collect and analyze information related to a transportation system's exposure, sensitivity, and adaptive capacity with regard to changes in the local or regional climate.

The vulnerability assessment should focus on those climate variables that will have the greatest effects on the local or regional transportation network. To determine which climate variables will affect the transportation network and to what degree, the vulnerability assessment team should examine the sensitivity of specific transportation assets to various climate and weather stressors, including families of stressors that in combination create a high-risk environment for transportation assets.

Figure 4. Trend of Annual Flood Magnitude from the 1920s through 2008



Geographic distribution of century-scale changes in flooding. The triangles are located at 200 stream gauges, which have record lengths of 85–127 years. The color and size of the triangles are determined by the trend slope of a regression of the logarithm of the annual flood magnitude vs. time for the entire period of record at the site, ending with water year 2008 (Source: Peterson et al. 2013).

Asset Sensitivity to Climate Stressor(s)

Sensitivity, which refers to how an asset or system responds when exposed to a stressor, is one of the three components of vulnerability, which also includes exposure and adaptive capacity. To analyze sensitivity, the vulnerability assessment team determines whether or by how much transportation assets could be affected by a specific stressor. This analysis can narrow the range of climate variables to study and focus resources on analyzing the stressors expected to cause the greatest harm to the transportation system or asset.

One way to determine asset sensitivity is by considering climate stressor thresholds—the magnitudes at which a specific climate stressor is most likely to disrupt, deteriorate, or damage the transportation system or asset. For the transportation sector, even relatively short duration extreme events can cause significant damage to infrastructure or disrupt operations. Changes to annual or seasonal averages can lead to long-term trends, such as changes in soil moisture, which can be important to consider for asset maintenance and replacement planning.

[17] Thomas C. Peterson et al., "Monitoring and Understanding Changes in Heat Waves, Cold Waves, Floods, and Droughts in the United States: State of Knowledge," American Meteorological Society, June 1, 2013, Accessed June 23, 2017, doi: **https://doi.org/10.1175/BAMS-D-12-00066.1.**

[18] Archfield, S. A., R. M. Hirsch, A. Viglione, and G. Blöschl (2016), Fragmented patterns of flood change across the United States, Geophys. Res. Lett., 43, 10,232–10,239, doi:**10.1002/2016GL070590.**

[19] Glenn A. Hodgkins, Paul H. Whitfield, Donald H. Burn, Jamie Hannaford, Benjamin Renard, Kerstin Stahl, Anne K. Fleig, Henrik Madsen, Luis Mediero, Johanna Korhonen, Conor Murphy, Donna Wilson, Climate-driven variability in the occurrence of major floods across North America and Europe, In Journal of Hydrology, Volume 552, 2017, Pages 704-717, ISSN 0022-1694, **https://doi.org/10.1016/j.jhydrol.2017.07.027**

[20] Karl, Thomas R., Jerry M. Mellilo, and Thomas C. Peterson. Global Climate Change Impacts in the United States. Report. 2009. Accessed June 23, 2017. **http://www.globalchange.gov/browse/reports/global-climate-change-impacts-united-states.**

[21] See footnote 13

[22] Kunkel, Kenneth E., et al. "Monitoring and Understanding Trends in Extreme Storms: State of Knowledge." Bulletin of the American Meteorological Society 94, no. 4 (April 1, 2013): 499-514. doi:10.1175/bams-d-11-00262.1.

[23] USGS. Landslide Hazards Program. Emergency Assessment of Post-Fire Debris-Flow Hazards. Available at **https://landslides.usgs.gov/hazards/postfire_debrisflow/index.php**

Exposure refers to whether the asset or system is located in an area experiencing direct effects of climate variables.

Sensitivity refers to how the asset or system fares when exposed to a climate variable.

Adaptive capacity refers to the system's ability to adjust to or cope with existing climate variability or future climate impacts.

The climate stressor thresholds to consider will be specific to asset types. An example of a specific threshold to consider for pavement may be the seasonal and annual frequency of future days and consecutive days over 95°Fahrenheit (F).

The following sections highlight several sources of information that an agency can use to determine which climate variables and thresholds are important to include it its vulnerability assessment.

Historical Performance and Agency Knowledge

An agency's past experiences with system/asset performance, especially during extreme weather conditions, can provide a foundation to identify the types of weather events and thresholds that cause impacts on transportation systems/assets. For example, if heat waves pose problems for transportation systems or assets in a specific geographic area, then any assessment should closely investigate temperature projections.

Some information on past performance can be gleaned from existing studies or data. For example, where sufficient data are available, maintenance, emergency management, and engineering logs can be consulted to determine the specific types of weather events that caused damage and disruption. This can range from the particular storm surge level that closed a bridge temporarily, to the levels of precipitation and stream flow that caused a culvert failure.[24] Maintenance records could also show connections between changes in pavement conditions and extreme heat events. Additional sources of information may include State and local hazard mitigation plans and/or data that are collected as part of the required periodic statewide evaluation of facilities repeatedly requiring repair and reconstruction due to emergency events (23 CFR 667).

District engineers, maintenance personnel, and DOT emergency managers are often very knowledgeable on the vulnerabilities of the current system. Eliciting their expert opinion is another way for agencies to identify the climate variables and thresholds that can impact the assets included in a vulnerability assessment. Information on past performance can also be combined with historical information about past weather events from NOAA's National Weather Service.

Infrastructure Design Standards and Guidelines

Another approach to identifying specific climate variables and threshold information is to assess the design standards and guidelines for a particular asset type. FHWA regulations (23 CFR 625 and 23 CFR 650.115) prescribe the allowable design standards and specifications for highways. These standards consist of quantitative values that can provide an indication of an asset's sensitivity to a particular climate variable, such as heavy precipitation or temperature fluctuations. Performing a sensitivity analysis on an asset can help reveal how that asset responds to changes in climate variables. For example, a sensitivity analysis of a bridge could help determine what flow quantities would result in overtopping, and how long before the end of service life that overtopping is likely to occur.

Photo © 123rf.com

It is important to recognize that typical historical climate conditions are unlikely to be representative of all future climate conditions. The climate is changing and future climate impacts may go beyond the range of impacts that occurred in the past.

[24] Caution should be exercised when equating a water surface level and the flow associated with that level to a "failure." Bridge closings or culvert failing events may be caused by issues such as debris being caught, upstream or downstream conditions, timing of peak flows in tributaries, or non-flow conditions, such rusted culvert bottoms. Conditions can also exist where assets fail at less than design flows due to flow obstructions or lateral stream instability.

Examples: Selecting Climate Variables and Sensitivity Thresholds

- **CAMPO** worked with State and local maintenance and engineering staff to estimate the thresholds at which specific extreme weather stressors are most likely to disrupt, deteriorate, or damage the transportation system. Thresholds included those based on design specifications as well as empirical, or observed, thresholds beyond which damage had occurred in the past.
- For FHWA's **Gulf Coast 2 Study,** the study team reviewed publications, records, and climate model results to identify variables needed for examining the resilience of all major transportation modes within the study region. Variables fell into the following categories: temperature, precipitation, sea level rise, and the storm surges associated with more intense storms. The project engaged transportation engineers, including hydraulic, structural, and coastal engineers, to help identify the climate projections and derived variables needed to conduct the analyses. For temperature and precipitation, the team identified variables focused both on averages (i.e., seasonal precipitation), and extremes (such as the 1% and 2% annual exceedance probability precipitation depths, maximum annual 7-day average air temperature) that would allow for comparison with engineering design thresholds.[25]

Resources for Identifying and Selecting Climate Variables

Transportation Climate Change Sensitivity Matrix, USDOT, 2015. The USDOT's Sensitivity Matrix documents the sensitivity of transportation modes and sub-modes (including roads, rail, airports, ports and waterways, and oil and gas pipelines) to 11 climate impacts: storm surge, wind, sea level rise/extreme high tides/coastal flooding, inland flooding, drought, increased temperatures and extreme heat, wildfires, dust storms, permafrost thaw, changes in freeze/thaw, and winter storms. Users may select a specific transportation mode and explore its sensitivity to a range of impacts, or they may select a specific climate impact and explore the sensitivity of different modes to that impact.

The Use of Climate Information in Vulnerability Assessments, FHWA, 2011. This memorandum focuses on the use of climate information when performing a vulnerability assessment. The memorandum describes several sources of precipitation and temperature information, and provides some recommendations on how this information can be used by transportation planners as they consider their climate-related vulnerabilities.

Synthesis of Approaches for Addressing Resilience in Project Development, FHWA, 2017. This report synthesizes lessons learned and innovations from a variety of recent FHWA studies and pilots to help transportation agencies address resilience concerns at the asset level in engineering-informed adaptation studies. Appendix B includes a summary of the derived climate change variables used in the various FHWA case studies.

[25] See section 2.2 of Climate Variability and Change in Mobile, Alabama (2013)

2 Obtaining Asset Data for the Vulnerability Assessment

After determining the study objectives and scope and identifying the assets and climate variables to study, the next step in the vulnerability assessment is to collect asset and climate data. Collecting data for a vulnerability assessment often requires consulting a variety of data sources that are not easily merged together. Not all data sets are of comparable quality or in an easily accessible format. For instance, facility elevation data may only exist in "as-built" diagrams stored on paper. Different pieces of information on facility condition might be found in a bridge database, in a pavement asset management system, or on paper copies of culvert inspection reports. The challenge of asset data integration may be a factor in determining what data to collect for the analysis. Here are a few considerations that may help simplify the asset data collection process:

- **Convene practitioners across localities, agencies, universities, and departments early in the process.** Various local governments, universities, agencies, and departments (e.g., mayoral offices, town planning offices, university climate or transportation centers, and public works, transportation, parks, and tourism departments) may maintain information that is not known to the assessment study team. Coordinating with these groups to help identify all existing data can reduce the need to collect new data or minimize the extent of data collection efforts.
- **Examine existing data and solicit internal knowledge.** Many practitioners will have access to a database such as a bridge or roadway inventory. Where data on major assets is lacking, maintenance and operations staff may be able to provide details on performance in both standard operating conditions and under specific weather events such as heavy rainfall, flooding, or storm surge. Practitioners can verify initial findings with site visits to assets that appear to be particularly vulnerable to the identified climate impacts.
- **Work within the bounds of the data.** It is easy to put together a "wish list" of data that would provide a clear picture of asset condition and sensitivity to conduct the vulnerability assessment; however, some of that data may not be readily available within the timeframe of the study. Study teams should use the best available data or focus data collection efforts on those that conform to the studies available resources and timeframes.
- **Use Geographic Information Systems (GIS) to collect, share, and analyze data.** Web-based GIS tools, such as ArcMap, allow practitioners to manage and display various datasets simultaneously. Mapping asset, traffic, and climate datasets, for example, can identify emerging hot spots and problem areas that may not have drawn the attention of maintenance staff.

ASSET TYPES, SOURCES, AND CHARACTERISTICS

The study objectives and scope will determine which asset data need to be collected. Table 1 summarizes the types of assets and asset characteristics that may be useful to collect data on in order to inform the vulnerability assessment.

Internal and external data may vary widely in age, quality, extent, and scale. Scale is a particularly important and challenging factor when comparing site-specific, State, and regional data.

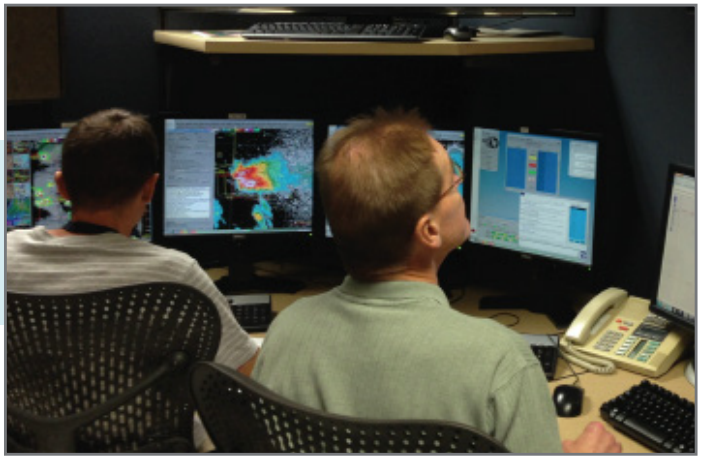


Photo © NOAA Photo Library

Table 1: Characteristics by Asset Type

Roadways	• Location (i.e., shapefiles) • Condition (i.e., materials, life of service, historical asset failure) • Geotechnical data (i.e., soil plasticity) • Function (i.e., Interstate, service road, evacuation route) • Annual average daily traffic (AADT) • Truck traffic volume
Bridges	• Location • Condition • Design thresholds and parameters (i.e., scour, inundation velocity/capacity)
Tunnels	• Location • Condition • Design thresholds and parameters
Airports	• Location (i.e., polygons, runway lengths) • Condition
Ports	• Location • Condition • Goods movement data
Culverts and flood control structures	• Location • Condition/Functionality
Signals, switches, and track	• Location • Condition/Functionality
Passenger rail	• Location • Condition • Average daily ridership
Freight rail	• Location • Condition • Goods movement data
Bus routes	• Location • Average daily ridership
Evacuation routes	• Location • Detour length
Traffic analysis zones	• Location • Travel volumes
Wetlands	• Location • Condition/Functionality (i.e., inundation velocity/capacity, water level)
Floodplain	• Extent of FEMA 100 and 500 year floodplains

Transportation agencies, including a State DOT, MPO, county, or municipality, likely track data on the major assets that will be a primary focus of the vulnerability assessment, such as roadways, bridges, and tunnels. In addition to these major assets, some vulnerability assessments may focus on smaller assets, particularly culverts, because they can have large impacts on a transportation network despite their relative size. Assets that the State DOT or MPO may not be directly responsible for tracking can impact the transportation network and the assets they oversee. If relevant to the scope of the vulnerability assessment, data on these assets should be collected from partner agencies.

Transportation agencies may not have as much data readily available on smaller assets and support structures, so the assessment may be a good impetus for designing mechanisms to track and record data on them.

Assets that the State DOT or MPO may not be directly responsible for tracking can impact the transportation network and the assets they oversee.

BEST PRACTICES FOR COLLECTING ASSET DATA

The previous section described the basic steps to begin collecting data for a vulnerability assessment, and provided examples of the assets, sources, and characteristics that may be useful in a vulnerability assessment. To improve data collection efforts in the future and realize the greatest benefits from the assessment, consider the following best practices:

- **Add vulnerability-specific data fields to regular asset management reporting.** Data that is missing at the start of a vulnerability assessment can be captured throughout the process and recorded for future assessments. For example, asset-level data such as culvert slope, waterway opening, and flood history can be incorporated in routine inspections and be useful for future assessments.
- **Implement specialized monitoring at high-risk sites**. The data collection process can identify high-risk areas that require more data to fully understand the risks and potential impacts. Flagging these sites for more frequent monitoring and data collection can help focus future vulnerability assessments and reduce the burden of State- or region-wide data collection efforts.
- **Consider using Light Detection and Ranging (LiDAR) systems to capture asset data.** LiDAR technologies can rapidly collect roadway asset data through a single effort that can be used for various purposes across different government agencies, but can be particularly useful for transportation planning, traffic operations, construction design, and maintenance activities. Using LiDAR data in a vulnerability assessment can help make the results more spatially explicit, which is useful for communicating to stakeholders.
- **Geo-code asset data as it is reported.** Similar to adding data fields to asset management reporting, another way to reduce the need for extensive data collection and survey efforts is to geo-code asset data when it is reported. When the condition of a particular asset changes (i.e., is damaged during a weather event or is upgraded following a routine maintenance visit), geo-code quantitative and qualitative information on the asset so it can be referenced as adaptation strategies are implemented or as local conditions change. This data may not be available at the beginning of a vulnerability assessment, but it can be useful for future assessments.

Photo © Bernie Roseke

Examples: Obtaining Asset Data for the Vulnerability Assessment

- **MTC** used an extensive online questionnaire to collect detailed data on 20 assets with 21 key asset components from agency staff. For example, one asset was a transit station and the associated key asset components were a traction power substation, a train control room, and a tunnel. The survey was comprised of 150 questions per asset and an additional 50 questions per asset component. In total, the survey included 3,000 questions on assets and potentially an additional 1,050 key asset component questions. The amount and nature of the questions made it difficult for MTC staff to complete the survey. Many adjacent assets were not owned or operated by members of the technical team, so many questions were left unanswered. Ultimately, detailed adaptation strategies were developed for five of the assets or key asset components as case studies, so much of the data was not used. MTC found it is important to balance how much data is collected in the early stages of a vulnerability assessment to determine which assets are most at risk against how much data is needed in later stages to appropriately develop adaptation strategies. MTC did geo-code all of the information, which will be useful in the future when assets are reexamined and adaptation strategies are developed.
- **For the statewide assessment (2011),** WSDOT found that its transportation asset inventory data was spread across multiple sources and varied widely in its level of detail and the extent of descriptive information included. As a result, the project team simplified asset data into large groups (for example highway corridors, not individual culverts) and converted the climate impact data into a format that could be used with agency asset data in the WSDOT's GIS tool. By bringing all data into a common tool, WSDOT was able interactively display the proximity of a variety of assets to a range of climate impacts, from sea level rise to wildfire risk. For its **2015 pilot study** of the Skagit River Basin, WSDOT was able to use all of its highway asset data to make profiles of each highway segment. **WSDOT** intended to leverage the efforts of a Federal flood study conducted by the U.S. Army Corps of Engineers (USACE). However, the USACE study was only partially completed and the flood scenario data were not fully available. WSDOT adjusted the scope of its pilot effort to use the information that was available from the USACE study, as well as hydraulic modeling and GIS data from local agencies.
- **CAMPO** assessed vulnerabilities to critical transportation assets throughout a six-county region in Central Texas. The study examined nine critical assets using available data and local expertise to assess their potential risk from extreme weather. During the assessment, CAMPO discovered that regional growth and other non-climate stressors can significantly influence extreme weather impacts. CAMPO looked at how the growth of heavy truck volumes and the expansion of impervious surfaces amplified the impacts climate variables had on the study assets. See section 5 for more information on how climate and asset data are used to assess the vulnerability of an asset or network.
- **The Maryland State Highway Administration** (SHA) assessed the vulnerability of its transportation assets (bridges and roads) to climate variables and stressors. Maryland SHA found data collection challenging because information on smaller culverts and drainage conveyances was limited and only available for counties that had permit requirements for reporting under the National Pollutant Discharge Elimination System. Using all available information, especially data collected from interviews and workshops with maintenance staff, SHA determined that it is important to consider flood control structures that are located in the vicinity of SHA transportation infrastructure during vulnerability assessments. Any failure or overtopping of privately or publicly owned flood control structures due to increased precipitation or storm surge could adversely impact downstream transportation infrastructure and increase their risk of failure. SHA found that data about the ownership and condition of flood control structures could be acquired through data sharing between State and county agencies.

3 Obtaining Climate Data for the Vulnerability Assessment

In addition to collecting asset data, the vulnerability assessment team also needs to obtain climate data for the study area in order to establish the projected future climate conditions to which assets will be (or are projected to be) exposed.

A variety of resources provide information on how to obtain data on projected changes in climate, depending on the type of climate variable and the level of detail needed for the vulnerability assessment. The following sections outline various ways agencies can obtain projections for changes in temperature, precipitation, hydrology, floodplains, sea level, and storm surge. Each section begins with a basic approach to obtaining climate data and then builds on that by adding more detailed methods that are useful for in-depth analyses. The level of detail in the analysis may vary depending on the type of agency decisions or actions that the assessment results will inform, as well as what the assessment budget allows.

Transportation agencies can benefit from partnering with other organizations that have experience developing or using climate projections, especially since these projections, models, and data sources are constantly evolving.

Coordinate with Partners to Obtain and Apply Climate Data

Depending on the objectives and scope of an assessment, different climate projections and climate data sources may be more or less relevant to a project. Transportation agencies can benefit from partnering with other organizations that have experience developing or using climate projections, especially since these projections, models, and data sources are constantly evolving. Especially for transportation agencies that have little experience with using climate projections, FHWA strongly recommends working with or communicating with climate science partners to ensure the correct application of tools and information.

Useful sources of information and assistance on climate data include:

- **Federal Science and Engineering Agencies.** Federal agencies, such as NOAA, U.S. Geological Survey (USGS), and USACE, may have relevant data, modeling, historic weather data, and future climate predictions.
- **National Research Organizations.** National research organizations such as the Transportation Research Board (TRB), National Cooperative Highway Research Program (NCHRP), and National Science Foundation study a variety of topics relevant to transportation agencies, including climate impacts and resilience.
- **University Climate Research Centers.** Universities may already be doing research on regional climate projections and may be able to provide available data or be interested in partnering to conduct a vulnerability assessment.
- **State and Local Agencies.** State and local environmental or other agencies may be able to help provide or develop necessary data. For example, local agencies may have access to LiDAR data or other data relevant to coastal mapping.
- **State Climatologist.** In some States, the State climatologist may be able to provide information on current climate research efforts and regional projections.

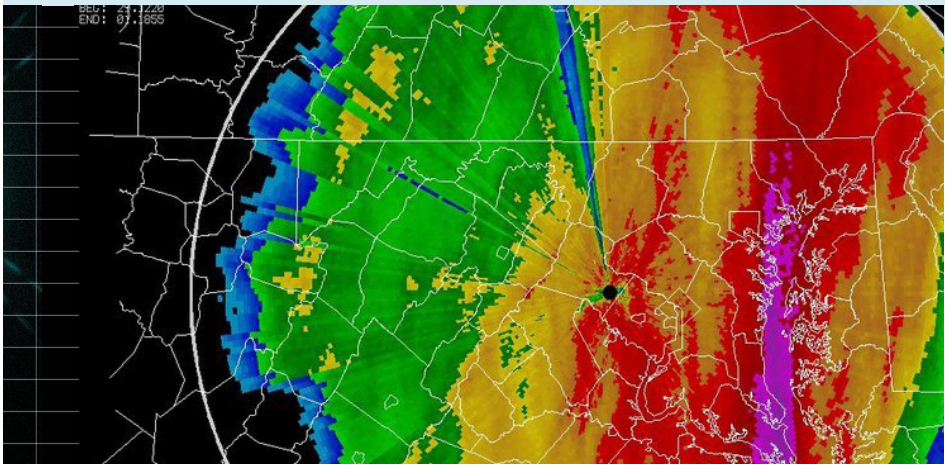


Photo © NOAA Photo Library

Understanding Climate Projections and Uncertainty

Whether relying on existing data and resources or developing tailored projections, it is helpful for those working on a vulnerability assessment to understand how climate projections are developed and the inherent uncertainty associated with future projections.

A global climate model is a mathematical representation of the interactions between and within the ocean, land, ice, and atmosphere. Climate models are "run" under an emissions scenario, which is generally based on a standard set of scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). Each of the scenarios in the IPCC's Special Report on Emissions Scenarios (SRES), the emission scenarios used in the IPCC's Third and Fourth Assessment Reports (published in 2001 and 2007, respectively), is based on different assumptions about population growth, economic growth, technological change, and policies that result in different growth rates of GHG and other climate-forcing emissions. The Representative Concentration Pathways (RCPs), the emissions scenarios used in the IPCC's Fifth Assessment Report (2014), are not associated with unique socioeconomic assumptions; rather, each RCP represents different trajectories of radiative forcing[26] levels over time. Of the four RCP scenarios, RCP 8.5 represents the highest emissions scenario while RCP 2.6 represents the lowest emissions scenario with immediate and sustained, aggressive GHG emission reductions. Each of the SRES and RCP scenarios represent a possible future. The IPCC does not suggest any single emissions scenario is more or less likely or probable to occur. Climate projections are generated for each emissions scenario for each climate model.

There is a degree of uncertainty associated with climate projections, due to three main sources:

- **Natural variability:** the unpredictable nature of the climate system
- **Model (scientific) uncertainty:** the ability to accurately model the Earth's many complex processes
- **Scenario uncertainty:** the ability to project future societal choices such as energy use

The relative contribution of each source of uncertainty to a climate model simulation's overall uncertainty varies across time periods. For example, the majority of uncertainty in near-term global projections (over the next 20 to 30 years) is from natural variability and model uncertainty, with scenario uncertainty contributing a relatively small amount. In contrast, the majority of the uncertainty for end-of-century global projections is due to scenario uncertainty. Model uncertainty plays a larger role for precipitation than for temperature. These uncertainties also change relative to each other for projections on different spatial scales. Natural variability becomes a greater source of uncertainty at finer scales. This is one reason why incorporating downscaled projections increases the potential uncertainty in climate projections.

Best practices for dealing with uncertainty include:[27]

- Use results from the full range of available global climate models to simulate the response of the climate system to human-induced change. Using results from multiple models will reduce the bias and uncertainty resulting from using just one climate model. However, if climate scientists determine that some models are more useful than others for the type of climate effect or location in question, it is preferable to use just those models.
- Examine and select climate projections associated with a range of emissions scenarios. Using the outputs from a range of scenarios ensures that the assessment is considering a range of possible futures rather than relying on any one single climate scenario (i.e., averaging across climate model results for a given emissions scenario). Note: The lowest scenario (RCP 2.6) generally should be avoided as it is overly optimistic compared to recent emissions trends. Rather than averaging results across scenarios, display and use the range of projections resulting from different scenarios so that the differences between the scenarios are evident.[28]
- Keep in mind there is little difference among scenarios in the near term, out roughly 20 years, in part because it takes a while for the difference in GHG emissions to build up and affect concentrations in the atmosphere. If the study objective is to analyze various timeframes, it is best to choose both near- and long-term timeframes such as 20, 50, and 80[29] years.

[26] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. It is used to assess and compare the anthropogenic and natural drivers of climate change. "2.2 Concept of Radiative Forcing." 2.2 Concept of Radiative Forcing - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing. 2007. Accessed June 23, 2017. https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-2.html.

[27] See the Gulf Coast Study Phase 2 Final Reports for additional information on dealing with uncertainty.

[28] Stott, Peter A., and J. A. Kettleborough. "Origins and estimates of uncertainty in predictions of twenty-first century temperature rise." Nature 416, no. 6882 (2002): 723-26. Accessed June 23, 2017. doi:10.1038/416723a.

[29] Most of the long-term available climate data projections are for the year 2099.

- Although climate model results have been made available for each day into the future, values are meant to be averaged over projected periods of at least several decades (i.e., 2020 to 2050) to reflect future climate conditions. The projected change for each climate simulation is obtained by taking the difference in modeled results between a future period and a historic period. The projected change is then "added" to the observed historic data (i.e., the observed historic data coincides with the modeled historic period). Climate simulation results are not meant to be used "as is" to reflect an observed or future condition for a brief window of time. It is very important that any climate analysis aligns with the purpose of climate models, providing changes in climate.
- Engage experts in climate science to express uncertainty based on the level of agreement and amount of evidence. In general, there is much more certainty regarding the direction of change than there is regarding the magnitude of change or the length of time it will take to reach a change. Experts can provide guidance on which impacts are fairly certain to happen this century, even if there is uncertainty regarding when those impacts will occur (Table 2).

Table 2: Likelihood of Global Climate Impacts

	Likelihood of Further Changes	
Phenomenon & Direction of Trend	Early 21st Century (2016-2035)	Late 21st Century (2081-2100)
Warmer and/or fewer cold days and nights over most land areas	Likely	Virtually certain
Warmer and/or more frequent hot days and nights over most land areas	Likely	Virtually certain
Warm spells/heat waves. Frequency and/or duration increases over most land areas	Not formally assessed	Very likely
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	Likely over many land areas	Very likely over most of the mid-latitude land masses and over wet tropical regions
Increases in intensity and/or duration of drought	Low confidence	Likely (medium confidence) on a regional to global scale
Increased incidence and/or magnitude of extreme high sea level	Likely	Very likely

Source: Adapted from the Intergovernmental Panel on Climate Change's *Climate Change 2013: The Physical Science Basis Summary for Policymakers*

TEMPERATURE AND PRECIPITATION PROJECTIONS

Transportation agencies typically use temperature and precipitation projections based on existing global climate models. Practitioners have several options for obtaining temperature and precipitation projections for their geographic area. These include:

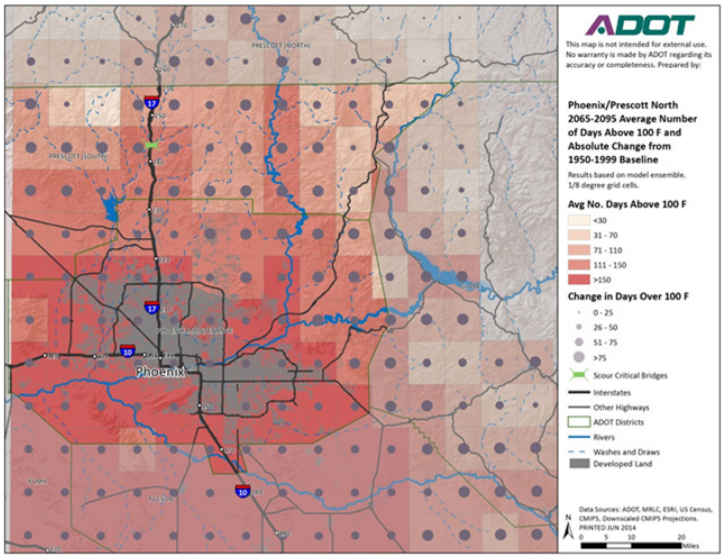
- **Use Existing Data and Resources on Regional Climate Change.** For general questions or for issues covering large areas, broad geographic information on projected changes in temperature and precipitation may be sufficient. Several reports, including the U.S. Global Change Research Program's National Climate Assessment, provide projections at this broader scale and information on the associated impacts on particular regions of the U.S. and sectors within those regions.
- **Use Existing Downscaled Data.** For other types of analysis—especially related to decisions about specific transportation assets—information on climate change for broad regions of the country may not be detailed enough. In such cases, practitioners can use more detailed information that has been processed to reflect local features/topography and conditions. Two general methods have been developed to reduce or "downscale" the spatial resolution of climate projections from

Downscaled data can be extremely valuable as inputs to high-resolution models (e.g., hydrologic models) for aspects of the environment (e.g., river dynamics, coastal processes) that affect transportation networks. However, the types of information they will add to the analysis should be established prior to expending significant time or cost in performing the downscaling.

[30] Climate models separate Earth's surface into a three-dimensional grid of cells. The results of processes modeled in each cell are passed to neighboring cells to model the exchange of matter and energy over time. Grid cell size defines the resolution of the model: the smaller the size of the grid cells, the higher the level of detail in the model. "Climate Models." Climate.gov. Accessed June 23, 2017. https://www.climate.gov/maps-data/primer/climate-models.

[31] See footnote 13

Figure 5: Projected Average Number of Days above 100°F for the Phoenix Metropolitan Area



Darker red areas of the map indicate a greater average annual number of days above 100°F, and larger circles in each grid cell indicate a greater change in days over 100°F annually. (Courtesy of AZDOT)

climate models: dynamic downscaling and statistical downscaling. Dynamic downscaling, often referred to as regional climate modeling, uses a limited-area, high-resolution model to simulate physical climate processes at the regional scale, with grid cells[30] typically 6 to 30 miles.[31] Dynamically downscaled models contain some uncertainty about the physical processes that occur at even smaller scales, such as the small watershed projects that are applicable to many transportation projects.

Statistical downscaling models develop historical relationships between large-scale weather and local observations to then apply in the translation of future projections down to the local scale. Statistical models are based on the assumption that the relationship between large-scale weather systems and local climate will remain constant over time. They are best suited for analyses that require a range of future projections that reflect the uncertainty in emissions scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes.[32] There are several different statistical downscaling processes, including bias correction constructed analogs (BCCA) and local constructed analogs (LOCA). The LOCA dataset is produced at a finer scale and is currently thought to be the preferred statistically downscaled dataset for precipitation.

Practitioners who need downscaled data should determine whether climate data have already been downscaled to their area. Some States and metropolitan areas have developed downscaled climate data for State or city climate action plans, and local universities may have developed data for research projects. Statistically[33] and dynamically[34] downscaled climate data for the contiguous U.S. are now publicly available online. Agencies can use the USDOT's **Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool** to process certain statistically downscaled climate data at the local level into relevant statistics for transportation planners.[35]

- **Develop projections tailored to study needs.** If the necessary information and data are not available from existing resources, agencies may choose to work with climate modelers to develop projections that are tailored to the study. While this approach is resource intensive, it can be useful to generate detailed information for the analysis.

Statistical models are based on the assumption that the relationship between large-scale weather systems and local climate will remain constant over time.

[32] See footnote 13

[33] Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections are available at **http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html**.

[34] Dynamically downscaled data is available from the North American Regional Climate Change Assessment Program (NARCCAP) at **http://www.narccap.ucar.edu/index.html**.

[35] U.S. Department of Transportation. CMIP Climate Data Processing Tool. Available at **https://toolkit.climate.gov/tool/cmip-climate-data-processing-tool**

Examples: Temperature and Precipitation Projections

- **ADOT** convened a workshop of scientific stakeholders to help the project team select and apply the most relevant and robust models, emissions scenarios, and downscaling techniques to the study area. The team selected future timeframes of 2025 to 2055 and 2065 to 2095 and used temperature and precipitation observations from 1950 through 1999. The project team used the USDOT CMIP Climate Data Processing Tool to retrieve climate data, eventually modifying the tool to facilitate processing larger batches of data and deriving a wider range of variables. Using the highest GHG emissions scenario to consider extreme temperature conditions, the selected climate models project increases of between 7° to 9°F in average daily maximum temperatures and increases in the average number of days above 100°F in the study corridor, regardless of land cover type (see Figure 5).
- **The Tennessee DOT (TDOT)** analyzed impacts from high and low temperature extremes, precipitation (including drought, flooding, snow and ice), wind, and tornados. The study team worked with researchers from the University of Georgia, using CMIP3 data to generate downscaled monthly averages of both precipitation and temperature for every county in Tennessee. The study team then used the USDOT CMIP Climate Data Processing Tool to provide a more detailed analysis of future precipitation and temperature extremes in the State's four major metropolitan areas. Finally, the team analyzed historic extreme weather data and performed a regression analysis to predict future patterns and trends for extreme weather scenarios that are not traditionally covered by future precipitation and temperature conditions.
- Using detailed statewide LiDAR data, **MnDOT** initially used Arc Hydro, an extension of Esri's Arc GIS software, to generate drainage areas for each asset. Arc Hydro created instances where water is conveyed through an embankment by a culvert that was not recognized in the LiDAR data, which was problematic for the analysis. MnDOT instead used StreamStats, a GIS web application created by USGS, to complete the analysis. StreamStats is less precise because it uses a coarser elevation dataset than the statewide LiDAR data, but it was sufficient for MnDOT's purposes.

Resources for Obtaining and Using Temperature and Precipitation Projections

Reports

Climate Change Impacts in the United States. U.S. National Climate Assessment, U.S. Global Change Research Program, 2014. This report assesses the science of climate change and its related impacts and responses by region and for various sectors, including transportation.

The Gulf Coast Study, Phase 2. Temperature and Precipitation Projections for the Mobile Bay Region, FHWA, 2012. This report describes a general approach for developing the projections needed to quantify future changes in temperature and precipitation exposure for any regional or sectoral analysis. It also describes the specific datasets and methods selected for and used in the analysis for the greater Mobile Bay region, including a description of the observational data, global climate models, future scenarios, and downscaling methods.

The Use of Climate Information in Vulnerability Assessments, FHWA, 2011. This memorandum focuses on the use of climate information when performing a vulnerability assessment. The memorandum includes discussion of using historical climate information and includes information on potential data sources.

Regional Climate Processes and Projections for North America, CMIP3/CMIP5 Differences, Attribution and Outstanding Issues, NOAA, 2014. This report summarizes the key differences and changes from CMIP3 to CMIP5.

Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience (Hydraulic Engineering Circular No. 17, 2nd Edition), FHWA, 2016. This document presents detailed technical guidance and methods for assessing the vulnerability of transportation infrastructure to extreme flood events in riverine environments. It includes information about downscaling climate data for use in hydraulic engineering.

Climate Model Comparison Tool: The Infrastructure and Climate Network (ICNet). This webpage provides detailed information on selecting the appropriate global climate model or collection of models for analysis.

Video: Downscaling global climate models. In this 47-minute video from FHWA's 2012 National Hydraulic Engineering Conference in Nashville, Tennessee, Dr. Katharine Hayhoe, Director of the Climate Science Center at Texas Tech University, describes the process of downscaling global climate models to regional scales.

Online Databases and Tools

Data sources that have projections of future climate change from many different models for various emissions scenarios include:

USDOT's CMIP Climate Data Processing Tool. This tool processes statistically downscaled climate model data from the World Climate Research Programme's CMIP3 and CMIP5 into relevant temperature and precipitation statistics for transportation

planners. These statistics include changes in the frequency of very hot days and extreme precipitation events and other climate variables that may affect transportation infrastructure and services in the near-term, mid-term, and end-of-century.

The U.S. Geological Survey's National Climate Change Viewer. The web viewer shows climate projections at the county and State level, based on statistically downscaled CMIP5 data for moderate and high emissions scenarios. This resource includes projections of climate variables based on daily high temperatures, low temperatures, and precipitation for near-term, mid-term, and end-of-century. In addition, these statistically downscaled projections were used to drive a simple water balance model to estimate runoff, snow, soil water storage, and evaporative deficit.

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections. This archive provides downloadable climate and hydrological simulations at fine spatial resolution from 1950 to 2099 (as well as climate and hydrological gridded observation data). It contains climate projections for the contiguous U.S., CMIP3 hydrologic projections over the western U.S., and CMIP5 hydrology projections over the contiguous U.S. This resource provides: statistically downscaled climate model data of high temperatures, low temperatures, and precipitation that is used by the USDOT CMIP Climate Data Processing Tool; soil moisture content, snow water equivalent, total runoff, and actual and potential evapotranspiration.

The U.S. Geological Survey's USGS Geo Data Portal. The data portal provides access to numerous climate datasets for particular areas of interest. Through the portal, users can create tailored projections for impact analysis by identifying the regional area and projection datasets of interest, along with a choice of treatment for averaging across model grid cells within the regional area.

North American Regional Climate Change Assessment Program (NARCCAP). The website provides access to a set of regional climate models (RCMs) driven by a set of atmosphere-ocean general circulation models (AOGCMs) over a domain covering the contiguous U.S. and most of Canada.

U.S. Geological Survey's StreamStats. This Web application incorporates GIS to provide users with access to an assortment of analytical tools that are useful for a variety of water-resources planning and management purposes, and for engineering and design purposes.

Websites that have historical weather and climate data available include:

- NOAA's **Climate.gov.** A source of timely and authoritative scientific data and information about climate.
- NOAA's National Center for Environmental Information, formerly the National Climatic Data Center. Provides access to an array of climate datasets at **www.ncdc.noaa.gov** and **www.ncdc.noaa.gov/climate-monitoring.**
- **NOAA's Precipitation Frequency Data Server (Atlas 14).** A point-and-click interface developed to deliver NOAA Atlas 14 precipitation frequency estimates and associated information.
- **US Historical Climatology Network data.** A data set of daily and monthly meteorological variables from observing stations around the contiguous U.S.

RIVERINE HYDROLOGY

Determining how streamflow and floodplains may change as a result of changing precipitation patterns is one of the most challenging tasks facing transportation agencies. As with projections of temperature and precipitation, there are several options for obtaining information on projected changes in riverine flood scenarios.

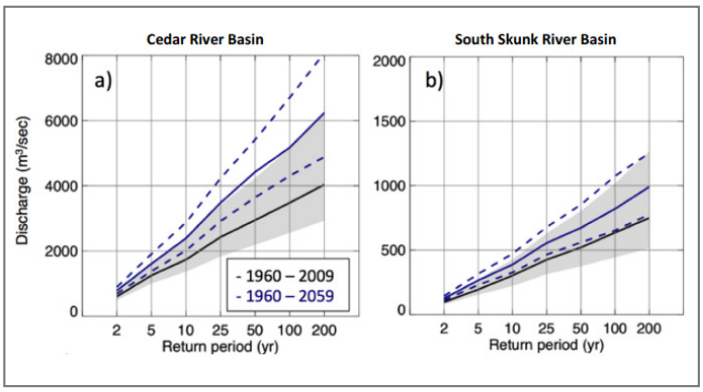
FHWA's **Hydraulic Engineering Circular No. 17, 2nd Edition** (HEC 17), describes five levels of analysis that can be used to assess the vulnerability of transportation infrastructure to riverine flooding. This analysis is based on calculating the estimated discharge, or flow, which is defined as the volume of water passing a given point per unit of time. The vulnerability assessment team should decide which level of analysis is most appropriate for the project based on data availability, team capability, and the service life of the assets under study (it may be more appropriate to conduct more detailed analysis for assets with a longer service life).

The five levels of analysis are:

- **Level 1 – Historical discharges:** Estimate the design discharge based on historical climate and watershed data, and then qualitatively consider changes in the estimated design discharge based on possible future changes in land use and climate change.[1] The future assessment of discharges is qualitative and primarily based on tools or data that show projected hydrologic trends for the area the transportation agency is analyzing. This type of analysis is most appropriate for assets with low failure risks and/or a shorter service life (less than 75 years).
- **Level 2 – Historical discharges/confidence limits:** For a Level 2 analysis, conduct a Level 1 analysis and then quantitatively estimate a range of potential discharges (confidence limits) based on historical data. Confidence limits[1] account for uncertainty in the hydrologic analysis by looking at a range of possible flows rather than a single point estimate. For assets with a longer anticipated service life, a larger confidence interval should be used. After developing the confidence limits, the team can conduct a quantitative resilience assessment of the assets using the full range of discharges from low to high confidence limits.
- **Level 3 – Historical discharges/confidence limits with precipitation projections:** This level builds upon the results of a Level 2 analysis by incorporating quantitative estimates for projected changes in precipitation (the T-year 24-hour precipitation value[1]) for the study area. The projected changes in precipitation serve as an indicator of the potential for climate change to affect the estimated design discharge (i.e., flood flows) based on historical data. Based on the projected changes in precipitation, evaluate whether a higher level of analysis is necessary. If this analysis finds that the effects of climate change on flow may be large, more detailed analysis as described in Levels 4 and 5 may be beneficial.
- **Level 4 – Projected discharges/confidence limits:** A Level 4 analysis builds on the work described in Levels 1 through 3 and incorporates future projections of climate using generally available downscaled climate projections, and where feasible, land use projections. Land use projections showing a range of future land use scenarios may be obtained from local or regional planning agencies. The design team performs hydrologic modeling using the projected land use and climate to estimate projected design discharges and confidence limits.
- **Level 5 – Projected discharges/confidence limits with expanded evaluation:** In Level 5, the most involved level of analysis, the team performs the equivalent of Level 4 analysis using site-specific custom land use and climate projections. At this level of analysis, more advanced hydrologic models might be justified. At Level 5, the design team should include individuals with appropriate expertise in climate science and/or land use planning. Figure 6 shows an example of the customized outputs from a Level 5 analysis using an asynchronous regression model[1] (ARRM) to downscale the daily precipitation data from a suite of specially selected climate models and emissions scenarios.

Planners and asset managers should contact their regional USACE office and local flood managers to determine if transportation assets have been included in recent flood studies, and to discuss potential for transportation assets to be included in future studies. This can improve coordination across agencies and reduce the level of effort required for future vulnerability assessments.

Figure 6: Current and Future Ranges for Quantiles of Peak Flow for Two River Basins Studied by Iowa DOT

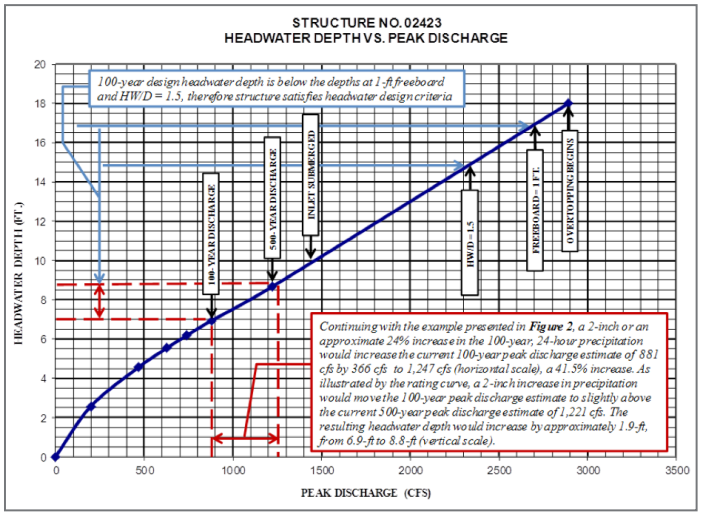


Iowa DOT downscaled daily precipitation projections using the ARRM, an example of a HEC 17 Level 5 analysis. This figure shows streamflow records from 1960-2009 (shaded area) and projected streamflow (dotted lines) for the service life of bridges in the Cedar River (left) and South Skunk River (right) basins. Increases appear to be more significant for Cedar River Basin than South Skunk River Basin. (Source: Iowa DOT)

Examples: Riverine Hydrology Analysis

- **The Connecticut DOT** (CDOT) (Level 2 analysis) conducted a systems-level vulnerability assessment of bridge and culvert structures 6 to 20 feet in length focusing on inland flooding associated with extreme rainfall events. The project team evaluated the hydraulic adequacy of the structures and developed rating (i.e., performance) curves illustrating the hydraulic performance of the structures over a range of flow conditions. Structures were determined to be hydraulically adequate if the hydraulic design criteria were satisfied for the current design discharge estimate (see Figure 7). If a structure was determined to be hydraulically adequate, CDOT assessed whether the structure had additional hydraulic capacity that would make it more adaptive to variations in the discharge estimate. This additional hydraulic capacity provides a cushion for uncertainties in the hydrologic/hydraulic calculations and for changes in precipitation and extreme weather events.
- **MnDOT** (Level 4 analysis) performed a system-level vulnerability screen, and then detailed analyses on two culverts using a range of climate scenarios. For the system-level screen, MnDOT calculated several hydrological metrics of vulnerability, including the percent change in peak design flow required for overtopping of each asset. This analysis provided a sense of the relative sensitivity of each asset to precipitation changes, and required less precise information about exactly how precipitation or flows may change in that location. MnDOT also calculated projected stream velocity, belt width to span length ratio, percent forest land cover in the drainage area, and other exposure metrics. For the site-specific analyses, MnDOT conducted hydraulic culvert analyses to evaluate the performance of the culverts under current and future peak flows. Peak flows through the culverts for several storm event return intervals and climate scenarios were modeled using the USDA-Natural Resources Conservation Service (NRCS) WinTR-20 program. The program calculates runoff based on drainage area, land cover, soils, time of concentration, and 24-hour precipitation.
- The **Iowa DOT** (Level 5 analysis) analyzed the potential impact of predicted future floods on six bridges to evaluate vulnerability. In order to simulate peak flow statistics of "Big Basins and Big Floods," the Iowa DOT incorporated rainfall simulations from global climate models into a highly detailed hydrologic model called CUENCAS to determine future peak discharge flows. The model independently calculated the percentage of daily rainfall that is absorbed into the soil and the percentage that is runoff for each unit of landscape. Because it is a continuous model, precipitation in the days or hours before a rainfall event is stored in the model. This allowed the study team to simulate and assess the impact of big storms when preceded by small events that increase the antecedent moisture content.

Figure 7. Flood Depth vs. Peak Discharge for a Structure in Connecticut



CDOT prepared headwater and velocity rating curves that show the hydraulic performance of the structures over a range of flow conditions. These rating curves can be used to evaluate the hydraulic adequacy and assess the adaptive capacity of a structure. (Source: CDOT)

Resources for Riverine Hydrology Analysis

Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience (Hydraulic Engineering Circular No. 17, 2nd Edition), FHWA, 2016. This document presents detailed technical guidance and methods for assessing the vulnerability of transportation infrastructure to extreme flood events in riverine environments.

COASTAL HYDROLOGY

Similar to the challenges of changing riverine hydrology, transportation agencies may want to consider the ways coastal hydrology may change as a result of sea level rise and changes in storm surge. This section discusses specific ways practitioners can begin to assess the potential risks and impacts of sea level rise and storm surge.

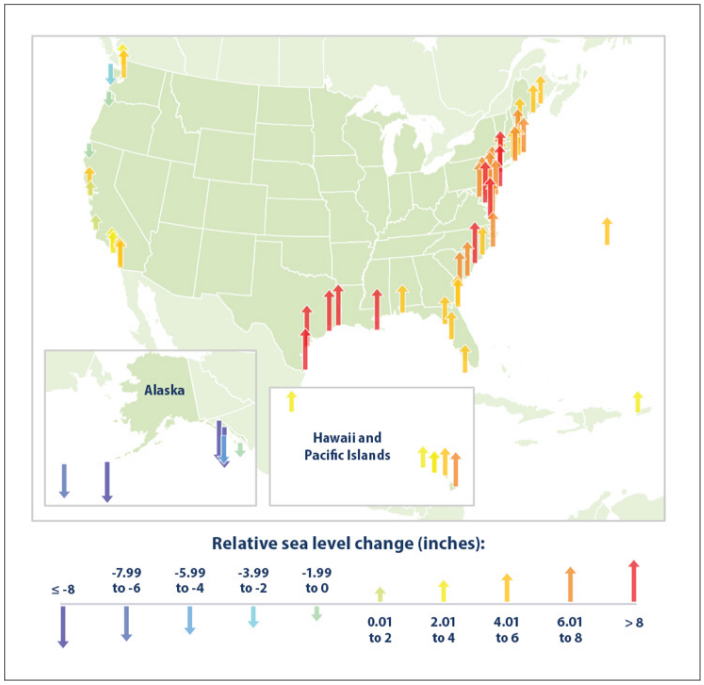
> If the sea level rise or storm surge mapping does not align with local knowledge of existing flooding, practitioners should carry out a thorough field visit to verify the vulnerabilities.

Sea Level Rise Projections

Projections of future sea level rise are based on global and relative sea level changes. Global sea level rise is the change in sea level predominantly due to thermal expansion from surface-level ocean warming and melting of glaciers and ice sheets. Relative sea level change accounts for both the global sea level rise and local factors such as subsidence (fall) or uplift (rise) of land (also called Vertical Land Movement),[40] ocean density, tidal patterns, and ocean circulation patterns.

Global sea level rise projections are available from a variety of sources, including the National Research Council (NRC), the National Climate Assessment (NCA), and NOAA. These analyses typically include a range of emissions scenarios and a range of projections to account for the uncertainties in the best available science.[41] For example, the 2014 NCA reports with very high confidence that, by end-of-century, global mean sea level[42] will rise between 8 inches and 6.6 feet, with 1 to 4 feet being most likely. NOAA reports that global mean sea level is likely to rise between 1 foot and 8.2 feet, depending on the emissions pathway followed.[43] Transportation agencies may wish to use multiple sea level rise scenarios in their analyses to understand their vulnerabilities under an upper-bound, worst-case plausible scenario, as well as under a mid-range, more likely scenario.

Figure 8: Relative Sea Level Rise along U.S. Coasts, 1960–2015



Cumulative changes in relative sea level from 1960 to 2015 at tide gauge stations along U.S. coasts. Relative sea level reflects changes in sea level as well as land elevation. 2016 update to data originally published in 2009. (Source: NOAA Technical Report NOS CO-OPS 053)

Sea level rise is expected to vary regionally due to local factors such as subsidence (see Figure 9). For example, the Northeast and Mid-Atlantic regions of the United States are expected to exceed the global average sea level rise due to local land subsidence.[44] Much of the Northwest coastline is rising due to tectonic uplift, so relative sea level rise is likely to be less than the global average.[45]

FHWA's **Highways in the Coastal Environment, Hydraulic Engineering Circular No. 25 – Volume 2** (HEC 25) provides detailed guidance on the methodology to calculate future projected sea level rise at a specific location. HEC 25 recommends that

[41] The range in the projections reflects uncertainty about how glaciers, ice sheets, ocean temperatures, currents, and winds will change over time. It is likely that the science of sea level rise projections will continue to evolve.

[42] Global sea level rise is based on mean sea level in 1992.

[43] "Global and Regional Sea Level Rise Scenarios for the United States." NOAA Tides & Currents. January 2017. Accessed June 23, 2017. **https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf**.

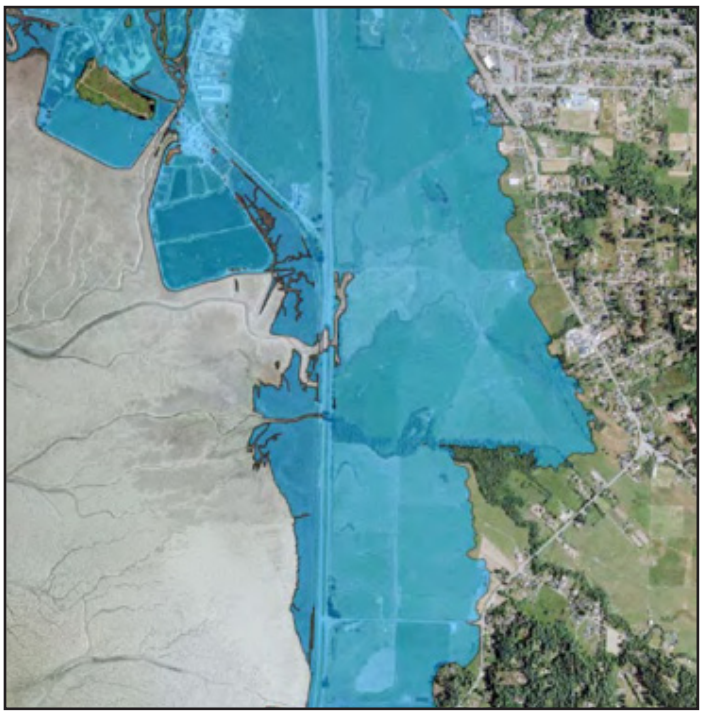
[44] See footnote 13

[45] See footnote 13

"best available science" be used when determining future sea level rise projections. It also cites, as best available science, an **online calculator** tool developed by the USACE that can be used to make sea level projections for any location under a variety of future sea level rise assumptions.

Some States and regions have requirements or recommendations for specific levels of sea level rise to use for planning purposes, including the States of California,[46] Massachusetts,[47] and New York.[48] These requirements typically outline the best available science for regional or statewide projected sea level rise, and establish consistent projections to use for analysis and planning. If such requirements do not exist, transportation agencies should use the best available science, technology, and information to develop or select sea level rise projections.

Figure 9: Modeled Flooding Conditions Caused by Sea Level Rise on California Highway 101



Caltrans modeled flooding conditions caused by sea level rise along California Highway 101 adjacent to Humboldt Bay. Models show that the southern reach of the highway will be regularly inundated by 2050, and by 2100, almost the entire six miles will be under water. These estimates considered MMMW and average King Tide conditions. (Source: Caltrans)

Examples: Sea Level Rise Projections

- The **Caltrans** team reviewed multiple sources for sea level rise estimates specific to northern California (see Figure 9). The team used data from NOAA's Sea Level Rise Viewer web mapping tool to assess frequent tidal inundation for existing and future conditions with sea level rise. Daily high tide and annual high tide, based on existing Mean Higher High Water (MHHW) and incremental increases, were used as approximations to identify sea level inundation areas. As recommended in the California Coastal Commission's published guidance on planning for sea level rise, the team adjusted the projections in the region to reflect tectonic conditions.
- The **Hillsborough MPO** study team relied on sea level rise projections from the Sea Level Scenario Sketch Planning Tool, an existing tool developed by the University of Florida. The tool includes statewide and regional projected rates of sea level change ("low/ historic," "intermediate," and "high" projections) in 10-year increments from 2040 through 2100. For its study, the Hillsborough MPO used the High and Low/Observed projections, and the Mean Higher High Water (high tide) was selected as the assumed tidal datum for all scenarios. These scenarios were selected collaboratively and reflect the expert judgment and risk tolerance of key partners in the region.
- The **Maryland** SHA study team worked with Salisbury University to develop fine-scaled sea level change data for each coastal Maryland County. To develop the local projections, the team used the best available LiDAR information to generate Digital Elevation Models for the study area. Each county was assigned a representative tidal station from which a locally observed Mean Sea Level and Mean Higher High Water was taken. Salisbury University used the tidal station values and the USACE sea level change rates to create county specific sea level change values for 2050 and 2100.
- **MTC** conducted refined SLR exposure assessments on three focus areas identified in MTC's first pilot study of vulnerable areas in the San Francisco Bay. MTC moved forward with data collection, exposure assessments, and strategy development concurrently, but found the exposure assessments should ideally have been completed first. This was not possible because the exposure assessments were time consuming, and they required unforeseen field visits to verify vulnerabilities. Some locations also required a second round of mapping and shoreline analysis. MTC is now aware of the time required to conduct detailed exposure analysis for future assessments.

[46] California Coastal Commission Sea Level Rise Policy Guidance. Report. August 12, 2015. Accessed June 23, 2017. **https://documents.coastal.ca.gov/assets/slr/guidance/August2015/0_Full_Adopted_Sea_Level_Rise_Policy_Guidance.pdf**.

[47] Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning. Report. December 2013. Accessed June 23, 2017. **http://www.mass.gov/eea/docs/czm/stormsmart/slr-guidance-2013.pdf**.

[48] "Part 490, Projected Sea-level Rise—Express Terms." New York State Department of Environmental Conservation. Accessed June 23, 2017. **http://www.dec.ny.gov/regulations/103877.html**.

Resources for Obtaining and and Using Sea Level Rise Projections

Reports

Global and Regional Sea Level Rise Scenarios for the United States, NOAA, 2017. The report presents a range of global mean sea level rise scenarios, and discusses projected relative sea level rise for different regions of the U.S.

North Atlantic Coast Comprehensive Study: Resilience Adaptation to Increasing Risk, USACE, 2015. This comprehensive study was conducted to address the flood risks of vulnerable coastal populations in areas that were affected by Hurricane Sandy (from New Hampshire to Virginia). The study includes an analysis of sea level and climate scenarios, and a discussion of how those scenarios might affect coastal populations, infrastructure, ecosystems, and implementation of risk management strategies within the study area. The report includes a nine-step Coastal Storm Risk Management Framework that was developed to help all stakeholders identify the risk of coastal flooding and evaluate the full range of strategies available to reduce those risks

Sea Level Rise for the Coasts of California, Oregon, and Washington, Past, Present, and Future, National Research Council, 2012. This report examines all aspects of relative sea level rise on the West Coast (including land mass movements). The study includes projections of sea level rise along the coast for the years 2030, 2050, and 2100, taking into account regional factors that affect sea level.

Photo © 123rf.com

Technical Guidance

Highways in the Coastal Environment: Assessing Extreme Events (Hydraulic Engineering Circular No. 25–Volume 2), FHWA, 2014. This manual provides technical guidance and methods for quantifying the exposure of transportation facilities to sea level rise, storm surge, and wave action.

Procedures to Evaluate Sea Level Change: Impacts, Responses and Adaptation, USACE, 2014. This technical letter provides guidance for understanding the direct and indirect physical and ecological effects of projected future sea level change on USACE projects and systems of projects, and considerations for adapting to those effects.

Incorporating Sea Level Change in Civil Works Programs, USACE, 2013. This regulation provides USACE guidance for incorporating the direct and indirect physical effects of projected future sea level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects.

Guidance on Incorporating Sea Level Rise, Caltrans, 2011. Provides guidance to Caltrans staff on how to assess the vulnerability of transportation projects to sea level rise impacts and incorporate adaptation into the programming and design of vulnerable projects.

Online Databases and Tools

Sea Level Change Curve Calculator, USACE. A tool that quickly estimates the relative sea level rise at a given location for each year until 2100, assuming certain rates of sea level rise and local land subsidence/uplift.

Digital Coast, NOAA. This NOAA-sponsored website provides coastal data and tools, including the **Sea Level Rise Viewer,** a Web mapping tool to visualize community-level impacts from coastal flooding or sea level rise. The viewer shows depth and extent of inundation for the entire U.S. coastline for six sea level rise scenarios, ranging from current (0 foot) to 6 feet (in 1-foot increments).

Video: **Forecasting Sea Level Rise for Maryland,** MD Sea-Grant, 2013. In this short video, scientists describe how subsidence in the Chesapeake Bay is impacting overall sea level rise in the area.

Storm Surge Analysis

Another stressor closely tied to sea level rise is storm surge, which is the amount of water that is pushed toward the shore during storms, combined with the effect of normal tides. Sea level rise increases the risk of damage from storm surge. Analyzing the effects of storm surge can involve examining past storms combined with projected future sea level rise and/or projected changes in storm intensity and duration. Storm surge scenarios can be developed from a number of different sources. Various methods may be appropriate, depending on whether the results will be used for an initial screen or to make project-level decisions.

FHWA's HEC-25 provides guidance on methodologies for assessing exposure of infrastructure to storm surge. Approaches, listed in order of level of effort, include:

- **Level 1: Use Existing Data and Resources:** This approach relies on established maps and tools to determine the degree to which a particular asset or area is exposed to the effects of extreme events and climate change. Agencies can use existing inundation information, such as FEMA flood hazard maps or tsunami hazard maps, to determine the exposure of infrastructure under selected sea level rise scenarios and the sensitivity to depth-limited wave or wave run-up processes. Transportation agencies are encouraged to work with State or local environmental counterparts to establish a set of sea level rise scenarios. As previously noted, in some cases, the State or local area may already have requirements or recommendations to consider sea level rise for specific future time periods.
- **Level 2: Modeling of Storm Surge and Waves:** If existing data is not available or is insufficient for the purpose of the assessment, an agency may choose to conduct original modeling of surge and wave fields using hydrodynamic models. Hydrodynamic models provide specific estimates of the critical regional coastal processes of interest, like water levels, wave heights and periods, velocities, etc. This type of analysis involves selecting extreme event and climate change scenarios appropriate for the study region; developing and validating suitable hydrodynamic modeling tools; simulating the extreme event and climate change scenarios chosen; mapping the hazards (i.e., inundation, waves, wave run-up) under each specific storm and climate change scenario chosen, and assessing exposure of infrastructure under each scenario. The development and application of hydrodynamic models, as well as the interpretation of their results, should generally be performed by a trained coastal engineer with expertise in hydrodynamic modeling.
- **Level 3: Modeling in a Probabilistic Risk Framework:** This approach, which characterizes exposure in terms of probability and consequence, requires running many (on the order of hundreds) simulations of surge, sea levels, currents, waves, or tsunamis, to determine the probability of events. Such an approach requires a significant investment of both time and financial resources. It requires expertise in coastal engineering, numerical modeling, hazard analysis, probability, and risk analysis. Accordingly, such studies should be performed by engineers with demonstrated expertise in modeling extreme events as well as an understanding of the appropriate regional climate scenarios.

Importance of Accurate Elevation Data

The utility and accuracy of a sea level rise and storm surge assessment depend, in part, on the resolution of the underlying elevation data. One standard source of elevation data, the USGS National Elevation Dataset (NED), supplies elevation data with a horizontal resolution of 30m and 10m and vertical resolution of around +/-2.4m. However, global projected sea level rise of up to 2m by the end of the 21st century falls within this +/-2.4m resolution. As such, maps based on the NED will generally not provide accurate predictions of exposure of specific assets. In order to obtain more useful elevation information, local assessments will likely need to rely on digital elevation models (DEMs) derived from high resolution LiDAR data. LiDAR, though not available in all locations, has become increasingly available for many areas in recent years. LiDAR data sets for many coastal areas can be downloaded from NOAA's Office for Coastal Management **Digital Coast.** Such data sets may require additional processing to use, including adjustments to the vertical datum to ensure consistency across data sets.[49]

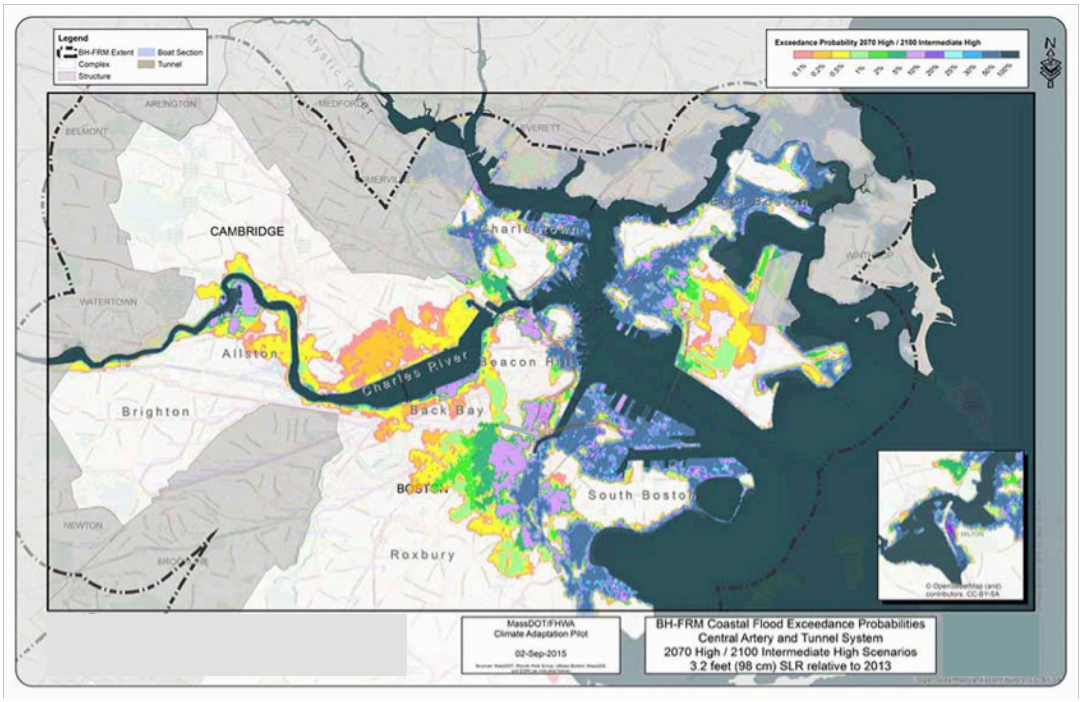
Processing LiDAR data can often be very resource-intensive in terms of both GIS expertise and computer processing time. However, agencies that used LiDAR data in their pilot projects agreed that its usefulness was worth the resources expended. It is important to use the latest LiDAR data available when mapping sea level rise and storm surge. As LiDAR is updated for more regions, check if recent data is available before beginning the vulnerability assessment.

[49] Adjustments to the vertical datum are a necessary part of mapping inundation. The land elevation data are usually referenced to a vertical datum called the North American Vertical Datum of 1988 (NAVD88). This data is not tidal, meaning that a value of "0" does not equate to any particular local tide value. Correcting this issue requires converting the elevation data from NAVD88 to a tidal datum, such as mean high tide (NOAA, 2011).

Examples: Storm Surge Analysis

- **MassDOT** sought to assess the vulnerability of the I-93 Central Artery/Tunnel system in Boston to sea level rise and extreme storm events. The study used the ADvanced CIRCulation (ADCIRC) model to analyze changes in coastal water levels, as well as the Simulating WAves Nearshore (SWAN) Model to simulate storm-induced waves in concert with the hydrodynamics (See Figure 10). The study team selected four time horizons to study—2013, 2030, 2070, and 2100—and developed scenarios simulating sea level rise along with the impact of hurricanes and nor'easters. The study team used a Monte Carlo50 statistical approach to develop:
  - » Depth of flooding information at tens of thousands of locations
  - » Detailed time-varying inundation maps
  - » Flood pathways and sources
  - » Probability of flooding in future years
- The first **MTC pilot study** identified the exposure of Alameda County to two SLR scenarios (16-inch and 55-inch) as well as a 100-year storm surge and a wind-wave scenario. There are large differences between the inundations for these two SLR scenarios, so MTC conducted a more refined analysis of each focus site's potential exposure to future SLR in its second pilot study. Using this refined methodology helped the project team understand the timing and onset of SLR and how it relates to flooding from existing storm events. It also helped the project team understand how to communicate the vulnerability to stakeholders. For example, Figure 11 demonstrates that high tide (MHHW) + a 24-inch SLR inundation scenario is equivalent to flooding from a five-year storm event under existing conditions. This is a powerful and understandable message especially for individuals who are not familiar with climate models. In scenarios where SLR or storm surge mapping did not align with local knowledge of existing flooding, technical teams, including field maintenance staff, conducted thorough field assessments. MTC also used critical path analysis to highlight how exposed areas of the pilot focus areas become inundated or flooded. Conducting a critical path analysis on the Bay Bridge focus area showed that all inland inundation on the south side of the bridge could be prevented by relatively simple strategies. This allowed MTC to focus on developing strategies for the north side of the bridge where water was overtopping broad stretches of the shoreline.

Figure 10: MassDOT Storm Surge Modeling Results



This map of the Boston area shows the probabilities of exceeding coastal flooding in the Central Artery/Tunnel system in 2070 with 3.2 feet (1 meter) of sea level rise relative to 2013. The majority of flood areas range from 1 to 50 percent probability of flooding. (Source: MassDOT)

[50] The Monte Carlo method is a type of simulation that explicitly and quantitatively represents uncertainty by repeating an analysis using a large number of different values for its critical parameters obtained by drawing repeatedly from their underlying probability distributions. By doing so, it generates a probability distribution of possible outcomes that incorporates the combined uncertainty surrounding each of these parameters.

Figure 11. Water Levels Associated with SLR and Extreme Tide Scenarios in the Hayward Focus Area

	Daily Tide	Extreme Tide (Storm Surge)						
Sea Level Rise Scenario	**Water Level above MHHW**	**1-yr**	**2-yr**	**5-yr**	**10-yr**	**25-yr**	**50-yr**	**100-yr**
Existing Conditions	0	15	20	24	27	32	36	41
MHHW + 6-inch	6	21	26	30	33	38	42	47
MHHW + 12-inch	12	27	32	36	39	44	48	53
MHHW + 18-inch	18	33	38	42	45	50	54	59
MHHW + 24-inch	24	39	44	48	51	56	60	65
MHHW + 30-inch	30	45	50	54	57	62	66	71
MHHW + 36-inch	36	51	56	60	63	68	72	77
MHHW + 42-inch	42	57	62	66	69	74	78	83
MHHW + 48-inch	48	63	68	72	75	80	84	89
MHHW + 54-inch	54	69	74	78	81	86	90	95
MHHW + 60-inch	60	75	80	84	87	92	96	101

Note: All values in inches above existing conditions MHHW at the Hayward Focus Area. The extreme tide levels above MHHW were derived from the FEMA MIKE 21 model output. Color coding indicates which combinations of sea level rise and extreme tides are represented by the mapping scenarios shown in Table 3-1. Cells with no color coding do not directly correspond to any of the mapping scenarios shown in Table 3-1.

This matrix of water levels associated with SLR and extreme tide scenarios in the Hayward focus area demonstrates, in the orange cells, how the impacts of potential SLR can equate to the impacts of a five-year storm event. (Source: MTC)

Resources for Storm Surge Analysis

Highways in the Coastal Environment: Assessing Extreme Events (Hydraulic Engineering Circular No. 25–Volume 2), FHWA, 2014. This manual provides technical guidance and methods for quantifying the exposure of transportation facilities to sea level rise, storm surge, and wave action.

FEMA Flood Map Service Center, FEMA. The official public source for flood hazard information produced in support of the National Flood Insurance Program.

North Atlantic Coast Comprehensive Study Report, USACE, 2015. USACE developed this report to help local communities better understand changing flood risks associated with climate change and to provide tools to help those communities better prepare for future flood risks. The report builds on lessons learned from Hurricane Sandy.

4 Assessing Vulnerability

In the transportation context, climate change and extreme weather vulnerability is a function of a transportation asset's or system's exposure to climate effects, sensitivity to climate effects, and adaptive capacity. Exposure refers to whether an asset or system is located in an area experiencing direct effects of climate change; sensitivity refers to how the asset or system fares when exposed to a climate variable; and adaptive capacity refers to the system's ability to cope with existing climate variability or future climate impacts.

In order to assess vulnerability practitioners will use the climate and extreme weather variables they developed (as described in section 4) to identify and evaluate the exposure, sensitivity, and adaptive capacity of a facility or system to determine its vulnerability to extreme weather and climate change. Risk, which considers the probability that an asset will experience a particular impact and the severity or consequence of the impact should also be incorporated when assessing vulnerability (see Section 5.3 for more discussion on considering risk). After identifying vulnerabilities, practitioners can then develop and prioritize measures to address such vulnerabilities.

The following sections outline three different approaches that practitioners can follow to assess vulnerability. The first two approaches described, stakeholder input and indicator-based desk review approaches, are primarily used for systems level or area analyses, while the third approach, engineering-informed assessments, focuses on a specific transportation asset. Each approach differs by the types of stakeholders involved, the forms of information required, the formats of the final vulnerability assessment findings, and/or scale. These approaches are not mutually exclusive; often a vulnerability assessment includes elements of each approach. Determining which approach is best for an agency depends on the agency's ultimate goal or goals for the vulnerability assessment and the resources available to conduct the assessment.

STAKEHOLDER INPUT APPROACH

A stakeholder input approach primarily relies on institutional knowledge to identify and rate potential vulnerabilities. Institutional knowledge draws upon local knowledge and experiences from nearby communities and on-the-ground public agency staff to assess a transportation asset's or system's exposure to climate effects, sensitivity to climate effects, and adaptive capacity. This approach allows practitioners to capture information that may not be apparent in records or desk-based analysis. The stakeholder input approach can help to create ownership and engagement among staff, which can be useful later on when the agency considers adaptation strategies for those assets deemed vulnerable and/or when it works to incorporate resilience into work processes and programs.

A stakeholder approach may involve conducting interviews with local transportation practitioners, such as maintenance and operations staff, engineers, and emergency responders. These individuals have local knowledge of how the study assets are used, and they have experience with what climate-related issues currently exist and how changes in climate may impact the assets. In addition to interviews, agencies can organize working sessions where local experts can compile and prioritize asset information based on their personal knowledge and experiences in the field. Useful group exercises could include mapping historical events; categorizing and weighting assets, particularly those perceived as most important or most vulnerable; and drafting thresholds for the types and severity of damages observed following extreme weather events. Local residents and business owners may also have historic knowledge of how climate stressors have affected assets during extreme weather events or over time, and should be included in interviews and surveys when possible.

A survey can be a useful tool for assessments with a large scope, such as a statewide assessment. A survey can be a cost-effective way to gather comprehensive qualitative data from a wide range of stakeholders. Depending on the results, the assessment can focus on specific geographic areas identified as problematic in the survey data. If the results reveal consistent concerns with certain asset classes statewide, the assessment can focus on common adaptation or mitigation strategies for specific assets.

The results of a stakeholder driven process are highly dependent upon the quality of stakeholder engagement. For workshops, the quality of facilitation, composition of attendees, and level of participation from experts are important factors in the ultimate success of the approach. Workshop participants should include experienced practitioners from a variety of disciplines, including asset management, maintenance, operations, emergency management, and engineering, as well as those with expertise in materials, hydrology, geology, and climate. It may also be beneficial to include local users of the asset. For surveys, the purpose and intended outcomes should be apparent to participants, questions should be brief and easily understood, and the results should be easy to aggregate into actionable findings.

Examples: Using a Stakeholder Input Approach to Assess Vulnerability

- **WSDOT** used a structured, stakeholder-based approach to qualitatively assess facility vulnerability. The study team held 14 regional and mode-specific workshops across the State. During the workshops, WSDOT staff rated all State-owned highways and other transportation assets for climate vulnerability. The workshop process involved over 200 staff, including subject matter experts in materials, hydrology, geology, and landscape architecture; maintenance staff; and State ferry, aviation, and rail system managers. WSDOT relied upon existing climate data produced by the University of Washington Climate Impacts Group. At the start of each workshop the study team presented impact maps that illustrated sea level rise, temperature change, and precipitation, wind, and fire threats to WSDOT infrastructure. These maps effectively communicated historical trends and projections to workshop participants. 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 (and other assets) for criticality and to rate the effect that projected changes in climate would have on WSDOT infrastructure. WSDOT synthesized the results from each workshop and produced a series of maps for each region showing the vulnerability ratings for road segments, airports, ferries, and rail lines.
- The **Oahu MPO** used three day-long group work sessions of an interdisciplinary study team to assess integrated risk to the five priority assets in their study from several climate change variables of concern, including sea level rise and shoreline erosion, changes in rainfall patterns, increases in storm surge intensity, and changes in cloud formation. At the work sessions, the team discussed the likelihood, magnitude, and consequence to society from climate change impacts on each asset. Facility operators and other subject matter experts described past responses of the facilities to natural disasters and emergencies.
- As part of a bilateral agreement to test U.S. and European climate analysis, FHWA and the Netherlands tested the Roads for Today Adapted for Tomorrow (ROADAPT) Quickscan process, a stakeholder-based process developed in Europe, on two road projects: one in the Washington State (SR167) and one in Holland (A58). In the Netherlands, Deltares, an independent research institute, convened the A58 project team, operations and maintenance staff, and local governments for three workshops using the agendas and processes outlined in the ROADAPT Quickscan methodology. During the workshops, participants used their intimate knowledge of the highway stretch to evaluate the consequences and likelihood of different weather impacts such as localized flooding from heavy precipitation and flooding from stream crossings. The team evaluated the risks for the road as well as the risks for the surrounding area the road serves.

INDICATOR-BASED DESK REVIEW APPROACH

An indicator-based vulnerability assessment approach provides a relatively low-cost way to score and rank transportation assets for vulnerability by relying on available data. It offers practitioners a big picture understanding of system-wide vulnerabilities and identifies where additional resources could be used to further distinguish asset-specific vulnerabilities.

Under an indicator-based desk review approach, a study team will use quantitative data on assets (e.g., elevation, geographic location, and existing flood protection) and projected climate stressors (e.g., sea level rise, temperature increases, and changes in streamflow) to serve as indicators to evaluate potential vulnerabilities. An indicator is a representative data element that can be used as a proxy measurement of the overall exposure, sensitivity, or adaptive capacity of a specific asset. As a reminder, exposure refers to whether an asset or system is located in an area experiencing direct effects of climate change; sensitivity refers to how the asset or system fares when exposed to a climate variable; and adaptive capacity refers to the system's ability to cope with existing climate variability or future climate impacts.

Useful indicators are those that help distinguish between assets, are based on relatively complete and consistent datasets (across assets being evaluated), and can be easily understood and interpreted. For example, in the **U.S. DOT Gulf Coast Study,** one goal of the assessment was to determine whether or not highways in Mobile, Alabama are vulnerable to rising temperatures. The assessment team identified the number of days per year with a recorded temperature above 95°F as an indicator to represent exposure. This decision was made because stakeholders indicated temperatures exceeding 95°F affected service, operations, and workforce conditions in the study area. In the same scenario, one indicator of sensitivity was truck traffic, since roadway segments with more or less truck traffic experience different effects during high temperature days. Lastly, one example indicator of adaptive capacity in this scenario was detour lengths. If detours for a specific segment are long, then the asset has less adaptive capacity than assets with short detours.

Once indicators are selected, the study team will compile data on them in order to identify which climate stressor is having or may have the greatest impacts on transportation assets. Climate projections developed in section 4 of this Framework can serve as exposure indicators; asset datasets identified in section 3 can serve as sensitivity and adaptive capacity indicators. Interviewing stakeholders who interact with various assets can provide necessary information regarding sensitivity and adaptive capacity that may not be apparent in, for example, bridge maintenance records or traffic reports.

The study team will need to develop an approach to convert indicator data into a single vulnerability score for each asset and for each climate stressor. A vulnerability scale ranging from 1–4, for example, is a simple way to categorize how assets will be affected by climate stressors; a 1 would be least vulnerable and a 4 most vulnerable. Develop an overall vulnerability score for each asset by weighting and combining the exposure, sensitivity, and adaptive capacity scores. Establishing a scoring approach will allow decisionmakers to review vulnerability rankings for each asset or climate stressor relative to other assets or stressors.

The results of the data-driven vulnerability screen provide transportation agencies with a starting point for understanding system vulnerabilities and making decisions on how to best manage those vulnerabilities. The study team should review the scores with knowledgeable stakeholders to ensure they reflect local conditions, and adjust the scoring approach as needed. Different stakeholders will likely have varying opinions on how to score assets and climate stressors, so it is important for them to review the results to identify places where the ratings could be incomplete or skewed. It may be beneficial to first rank assets or segments by level of exposure, and once this ranking is established consider prioritizing by sensitivity and adaptive capacity.

Involve knowledgeable stakeholders throughout the process. An indicator-based approach will never perfectly capture local circumstances or asset-specific details. Involving knowledgeable, local stakeholders, such as maintenance staff, emergency managers, and engineers, in each step, from the selection of indicators, to scoring the assets, to vetting the preliminary results, can be useful for refining and improving the indicators and scoring system.

USDOT developed the **Vulnerability Assessment Scoring Tool** (VAST) to assist users with conducting a quantitative, indicator-based vulnerability screen of large numbers of assets. VAST is a spreadsheet tool designed to take users through the scoring process in a systematic, results-driven manner.

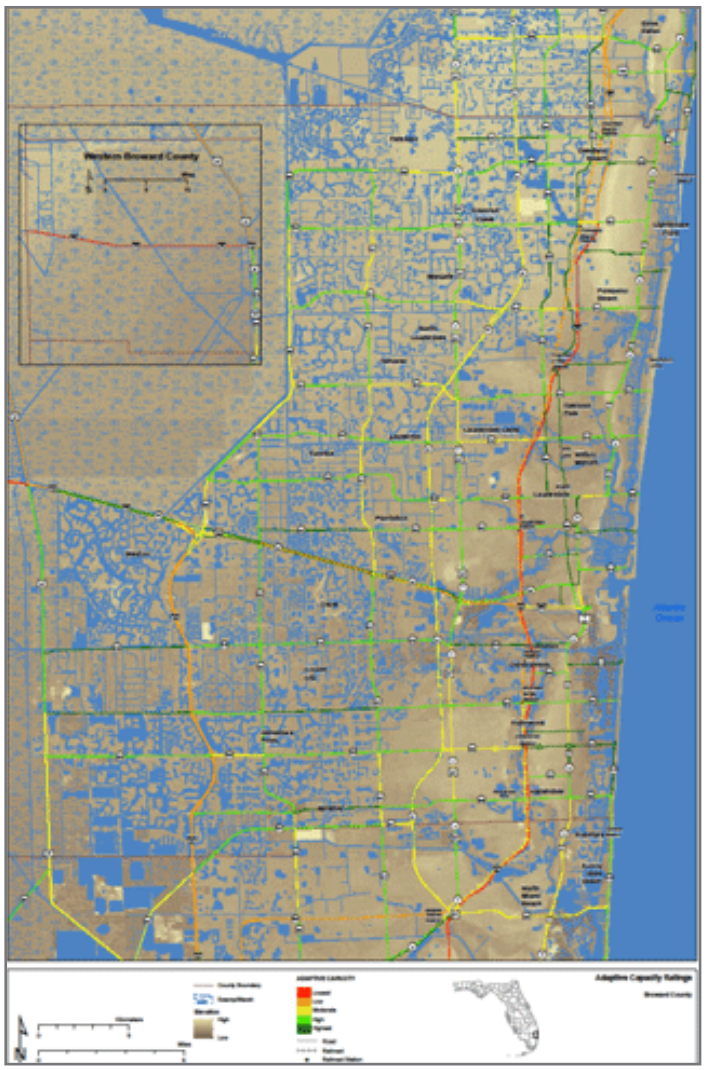
The indicator-based, desk review approach is often combined with the stakeholder approach; combining both approaches, in different combinations that reflect stakeholder goals, can lead to more useful results. For example, a desk review approach can provide a structured starting point to identify an initial list of vulnerable assets, and the results generated can then be used to inform and elicit feedback from stakeholders and local experts. Data, including projections, can be verified by local transportation staff and members of the public who have observed circumstances in the field. Alternatively, a stakeholder process can precede an indicator-based process. For instance, the ROADAPT framework starts with a stakeholder-based process called a QuickScan to identify the primary climate risks and damage mechanisms. The next step in ROADAPT is an indicator-based approach that ranks the vulnerability of specific assets relative to one another.

Examples: Indicator-Based Desk Review Approach to Assess Vulnerability

The **Southeast Florida** pilot team calculated vulnerability scores for each network segment in the study area using indicators for exposure, sensitivity, and adaptive capacity. The team then calculated vulnerability scores for each segment as a weighted average of its exposure, sensitivity, and adaptive capacity and mapped them (see Figure 12). They originally found that the exposure variable was being overwhelmed by the scores of the other variables. To correct for this, the team chose to weight exposure higher than the other two categories, because they observed that exposure is a threshold factor, and adaptive capacity and sensitivity are not important if an asset is not exposed to the climate stressor(s). The indicators used include:

- *Exposure:* The project team used three indicators to calculate each segment's exposure score: (i) the percentage of the segment permanently inundated by 1, 2, or 3 feet of sea level rise by 2100, (ii) its current "flood inundation exposure index" (measured by storm surge and precipitation), and (iii) its future "flood inundation exposure index."
- *Sensitivity:* The team used bridge scour rating and substructure condition rating as indicators of sensitivity for roads. The project team did not evaluate sensitivity for rail assets, since no relevant data were available.
- *Adaptive capacity:* The team considered average annual daily traffic and detour length for roads, and Tri-Rail ridership—a commuter rail line linking Miami, Fort Lauderdale, and West Palm Beach, Florida.

Figure 12. Map of Adaptive Capacity of Broward County, Florida Roads



The Southeast Florida team developed maps showing adaptive capacity and vulnerability scores for each road segment. The map above shows the adaptive capacity ratings for Broward County. (Source: Broward MPO)

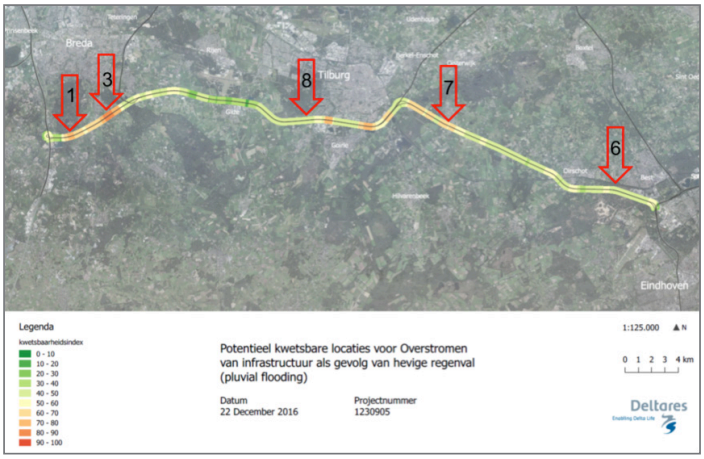
- **Maryland SHA** used a two-tiered assessment approach that included a high-level desk review and a detailed quantitative assessment. First, the team used a desk review to screen out assets in the study areas that were at low risk of exposure to the selected climate stressors. Next, Maryland SHA conducted detailed vulnerability assessments of individual assets in the vulnerable areas. They used VAST to evaluate bridges and large culverts and they developed a Hazard Vulnerability Index for roads. A workshop with agency engineers to match the Maryland climate and asset context to appropriate vulnerability indicators helped inform indicator weighting. The workshop participants ranked the severity of an asset's anticipated failure from a given climate stressor. More weight was given to indicators with the highest averaged rankings and to those with higher quality data available.
- **MnDOT** developed a set of vulnerability indicators for exposure, sensitivity, and adaptive capacity to understand assets' vulnerability to floods. The study team scaled each of the indicators on a 0- to 100-point scale. The study team then weighted the indicators, using higher weights for indicators perceived as more important to characterize vulnerability. The study team combined the weighted indicators to produce composite exposure, sensitivity, adaptive capacity, and vulnerability scores for each asset (see Figure 13). The study team identified statistical clusters in the data distribution and grouped assets with similar scores into five tiers of vulnerability.
- As part of FHWA's cooperation with the Netherlands researchers at Rijkwaterstaat (RWS), the Netherlands' Ministry of Infrastructure and Environment, the team developed vulnerability scores for sections of the A58 highway in Holland using ROADAPT's Vulnerability Assessment (VA) and FHWA's VAST. The team combined data sets from Alterra Research Institute, Blue Spot (an earlier flood risk analysis performed by RWS), a site visit assessment, road drainage system records, elevation difference between the road and the surrounding area, and the presence of culverts and ditches to evaluate vulnerability (see Figure 14). The rankings generated by the VA and VAST tools were similar, though not identical.

Figure 13: MnDOT Vulnerability Scoring Process for a Large Culvert

Variable	Value for the Example Asset	Range of Values Across All Assets		Scaled Value for the Ex Asset (0-100)	Variable Weight	Score
		Low	High			
Sensitivity						
% change in design flow required for overtopping	-18%	-78%	2375%	98	60%	58.5
Channel condition rating	6	–	–	50	15%	7.5
Culvert condition rating	5	–	–	50	25%	12.5
				Sum of Sensitivity Variable Scores:		78.5
				Sensitivity Weight:		33%
				Final Sensitivity Score:		25.9
Exposure						
Stream velocity	7.01	0.74	37.53	17	20%	3.4
Previous flooding issues	1	0	1	100	35%	35
Belt width to span length ratio	3.68	0.32	209.24	2	10%	0.2
% forest land cover in drainage area	1.85%	0.00%	91.23%	2	10%	0.2
% of drainage area not lakes and wetlands	99.91%	97.71%	100.00%	96	10%	9.6
% drainage area urban land cover	4.00%	0.00%	53.52%	7	15%	1.1
				Sum of Exposure Variable Scores:		49.5
				Exposure Weight:		33%
				Final Exposure Score:		16.3
Adaptive Capacity						
Average Annual Daily Traffic (AADT)	5,700	90	49,200	11	35%	4
Heavy Commercial Average Daily Traffic (HCADT)	610	5	5,900	10	25%	2.6
Detour Length	0.6	-0.37	20	4	35%	1.3
Flow control regime	0	0	1	0	5%	0
				Sum of Adap. Cap. Variable Scores:		7.8
				Adaptive Capacity Weight:		33%
				Final Adaptive Capacity Score:		2.6
				OVERALL VULNERABILITY SCORE:		45

MnDOT scaled and weighted indicators of sensitivity, exposure, and adaptive capacity of assets under study to create vulnerability scores. This allowed MNDOT to group assets into vulnerability tiers. (Source: MnDOT)

Figure 14: Locations Vulnerable to Flooding along the A58 Highway



Output from GIS-based ROADAPT tool showing sites potentially vulnerable to pluvial flooding. Green indicates relatively low vulnerability while orange indicates relatively high vulnerability. Arrows indicate areas of highest vulnerability and contain reference numbers which match to the site names. (Source: Deltares).

Resources for Assessing Vulnerability

Video: ***Identifying and Rating Vulnerabilities.*** In this short video, Sandy Salisbury, roadside and site development manager for WSDOT, describes how WSDOT conducted its vulnerability assessment through regional workshops.

2013–2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned, and Recommendations. Over the course of two years, FHWA worked with State DOTs and MPOs to undertake 19 assessments of climate change and extreme weather vulnerability and adaptation options on their transportation systems. The pilots used and built on FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework. This report highlights results and lessons learned from those efforts.

Vulnerability Assessment Scoring Tool (VAST). USDOT, 2015. This **Excel spreadsheet** tool provides step-by-step guidance through the process of conducting a quantitative, indicator-based vulnerability screen. Users enter information on their assets, select the parameters for the analysis, and select indicators to evaluate exposure, sensitivity, and adaptive capacity. The tool then calculates vulnerability scores for each asset on a scale of 1 to 4. The VAST tool was developed to facilitate screening or scoring of a large number of assets; the user can then decide whether a more in-depth analysis is needed on specific vulnerable assets identified through VAST.

The Gulf Cost Study: Screening for Vulnerability, FHWA, 2014. This report describes the methodology and findings of a high-level vulnerability assessment of the transport system in Mobile, Alabama. This analysis used an indicators approach that scored assets and climate stressors against exposure, sensitivity, and adaptive capacity indicators. Then, an overall vulnerability score for the asset to the climate stressor was developed by weighting and combining the exposure, sensitivity, and adaptive capacity scores. Stakeholders also vetted preliminary results to ensure key assets that did not score as high were included. Detailed information on the scoring and weighting systems used for each indicator is included in the Appendices.

ROADAPT, Guideline B: Performing a Quick scan on risk due to climate change, Conference of European Directors of Roads (CEDR), 2015. The Quickscan approach is a method for performing a preliminary climate change risk assessment that uses three desktop planning efforts and three workshops to identify consequences, probabilities, risk, location, and an action plan for roadways. The process results in a short list of locations that will receive action plans, which can include new actions or existing activities that take place in operations and maintenance activities. Suggested stakeholders to involve in the Quickscan approach include transportation experts, economists, road engineers, communications experts, climate specialists, and asset operators.

ROADAPT, Guideline C: GIS-aided vulnerability assessment for roads, Conference of European Directors of Roads (CEDR), 2015. The ROADAPT Vulnerability Assessment (VA) combines multiple indicators of climate change vulnerability in a GIS-based format to evaluate the vulnerability of road segments or assets relative to one another.

ENGINEERING INFORMED ASSESSMENTS

Engineering-informed adaptation studies are characterized by a greater level of asset specific data and analysis than a broader assessment that assesses multiple assets. A detailed engineering assessment offers a way to evaluate risks to particular transportation assets in response to climate stressors. Engineering assessments that consider future climate change are integral to identifying where and to what extent assets may incur damage from climate stressors. These assessments also help agencies anticipate the effectiveness of specific adaptation measures and their respective return on investment if adopted.

A detailed engineering assessment mirrors many of the elements of a systems-level assessment but is tailored to a specific facility or asset. An engineering assessment involves the following elements:[51]

- **Understand site context and future climate.** The context of a particular asset, including its design life, function within the broader transportation system, and location within the natural environment, can help determine the appropriate scope and scale of study. Considering how the climate at the site may change in the future allows practitioners to understand potential risks to the asset.
- **Test the asset against future climate scenario(s).** Evaluate the asset or proposed asset to determine how it would perform under projected climate change scenario(s).
- **Develop, evaluate, and select adaptation measures**. If the asset will be negatively impacted by climate change, identify plausible adaptation strategies, and then evaluate their efficacy under the future scenario(s). Selecting the appropriate adaptation measure(s) to implement may depend on both efficacy and cost.
- **Review additional considerations.** When deciding on adaptation strategies, consider how the asset contributes to the broader transportation network and relates to the environmental setting. Socioeconomic, budgetary, and political considerations may also affect which strategies are selected.
- **Monitor and revisit as needed.** Revisit the decision on adaptation strategies as the asset context and/or future climate conditions begin to change.

Examples: Engineering Informed Assessment

- As part of the Gulf Coast 2 Study, FHWA conducted detailed engineering assessments on 10 facilities in Mobile, Alabama to demonstrate the application of the process on a range of transportation asset types, including culverts, bridges, tunnels, piers, and pavement, and climate change stressors. One of the assets analyzed was the Airport Boulevard Culvert (see Figure 18). The project team evaluated whether the culvert design was sufficient under projected levels of 24-hour precipitation. Using projected 24-hour rainfall values and NOAA temporal rainfall distributions, peak flows to the culvert were modeled using the Win TR-20 Program, considering both existing and future land use conditions. Hydraulic analyses were then conducted to determine the performance of the culvert under current and future flows, using the HY-8 Version 7.2 program. Performance was assessed by determining whether at least 2 feet of freeboard would be achieved during a 25-year annual exceedance probability (AEP) event, which is the standard used by the city of Mobile for this type of culvert. For each adaptation option, flooding impacts of a 100-year event on surrounding areas were evaluated. An economic analysis of adaptation options was conducted using a Monte Carlo process.
- FHWA partnered with State DOTs and local transportation agencies in the New York-New Jersey-Connecticut region to conduct an engineering-based extreme weather and climate change vulnerability and risk assessment on 10 assets in the tristate region. One asset was the Loop Parkway Bridge, a limited access facility used heavily by commuters between the barrier island communities of Long Beach, Lido Beach, and Point Lookout to Long Island, New York. The bridge has demonstrated vulnerabilities to coastal flooding that may worsen due to projected sea level increase as the century progresses. The specific bridge components considered in the assessment included the electrical and mechanical systems, and the specific climate stressors considered were sea level rise, storm surge, and extreme heat events.

Figure 15. Airport Boulevard Culvert over Montlimar Creek in Mobile, Alabama

The Gulf Coast study examined culvert designs, such as the one pictured above from Airport Boulevard in Mobile, Alabama, to determine how they would perform in future flood scenarios. (Source: FHWA)

[51] Synthesis of Approaches for Addressing Resilience in Project Development (2017), FHWA, Section 3.3. Available at https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm

Resources for Conducting Engineering Informed Assessments

Synthesis of Approaches for Addressing Resilience in Project Development, FHWA, 2017. This report provides lessons learned for a range of engineering disciplines when considering climate change and extreme weather events in engineering and also discusses analytical processes for addressing climate change and extreme weather events in project level assessments. This work was based on multiple engineering-informed adaptation studies that sought to address climate change concerns, including nine that were conducted as part of this project with a range of State partners.

Post Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, FHWA, 2017. This final report from the study includes information on damage and disruption from Hurricane Sandy on the region's transportation systems, along with that of Hurricane Irene, Tropical Storm Lee, and Halloween Nor'easter Alfred. The report also includes engineering-informed assessments of climate vulnerabilities and risks and evaluation of potential adaptation strategies for a selection of transportation facilities—roads, bridges, tunnels, rail, and ports—that can be considered for these and similar facilities.

The Adaptation Decision-Making Assessment Process (ADAP), FHWA, 2017. ADAP is an 11-Step process that was developed to structure the asset level analyses conducted as part of the TEACR project. Its steps fit well with the elements listed in section 5.4.

Engineering Assessments of Climate Change Impacts and Adaptation Measures, FHWA, 2014. This report discusses a series of engineering assessments on specific transportation facilities in Mobile, Alabama that evaluated whether those facilities might be vulnerable to projected changes in climate, and what specific adaptation measures could be effective in mitigating those vulnerabilities.

CONSIDERING RISK

In addition to considering exposure, sensitivity, and adaptive capacity, practitioners should also incorporate risk when assessing a transportation asset's or system's vulnerability. Risk is a measure that includes both the probability that an asset will experience a particular impact, and the consequence (or severity) of that impact. While probability of an impact may be low in certain circumstances, the severity of an impact may be high, and conversely, high impact probability scenarios may have low severity. Identifying and understanding the probabilities and severity of climate change risks can help agencies make more informed decisions about the costs and benefits of potential adaptation and mitigation options in the future. See section 6.2.4 for more details on incorporating risk into an economic analysis of adaptation options.

Due to the nature of climate projections, determining the probability or likelihood of future climate impacts is problematic; it is not possible to apply a particular likelihood to a climate scenario. As explained in section 4 (see the text box Understanding Climate Projections and Uncertainty), there are a variety of best practices for dealing with the uncertainty of climate projections, including examining and selecting climate projections associated with a range of emission scenarios—including "low emissions" and "high emissions" scenarios. Doing so provides a broad frame of reference for when and how to incorporate risk into decisionmaking. Agencies can also conduct more detailed analysis on the likelihood of impacts by generating probability distributions of possible outcomes.[52]

To determine the consequence of projected impacts, agencies should consider the level of use of an asset, the degree of redundancy in the system, and/or the value of an asset (in terms of cost of replacement, economic loss, environmental impacts, cultural values, or loss of life).

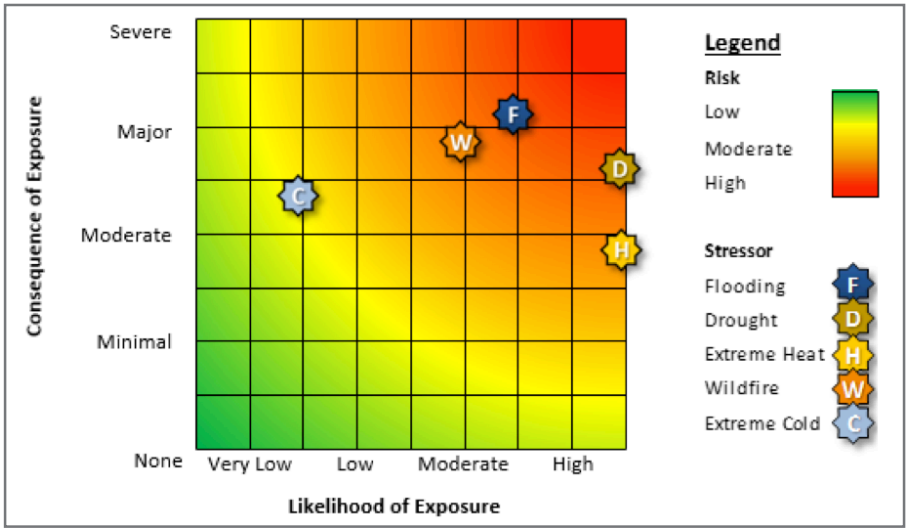
Risk is often represented by a matrix that classifies climate stressors into categories (i.e., low, moderate, or high) based on their likelihood and consequence (see Figure 16). With information on consequence and likelihood, agencies can categorize assets into the following groups:

- *Low risk:* Assets that have a low likelihood of being impacted by a future climate condition and a minimal consequence of being impacted by that condition.
- *Moderate risk:* Assets that have a low likelihood of being impacted by a future climate condition and a major consequence of being impacted by that condition.
- *Moderate risk:* Assets that have a high likelihood of being impacted by a future climate condition and a minimal consequence of being impacted by that condition.
- *High risk:* Assets that have a high likelihood of being impacted by a future climate condition and a major/severe consequence of being impacted by that condition.

Agencies can use the risk analysis to develop a prioritized list of assets that are vulnerable to future climate impacts.

Consider training staff on how to conduct risk-based planning. Incorporating risks, particularly those related to climate projections, can be challenging. Agencies should train staff on how to effectively incorporate risks into the planning, design, construction, and maintenance of new and existing infrastructure. While routinely incorporating traffic projections into facility design, engineers typically have limited experience with using climate projections to inform design decisions, since they rely on statistically-derived historical climate data.

Figure 16: CAMPO Risk Matrix



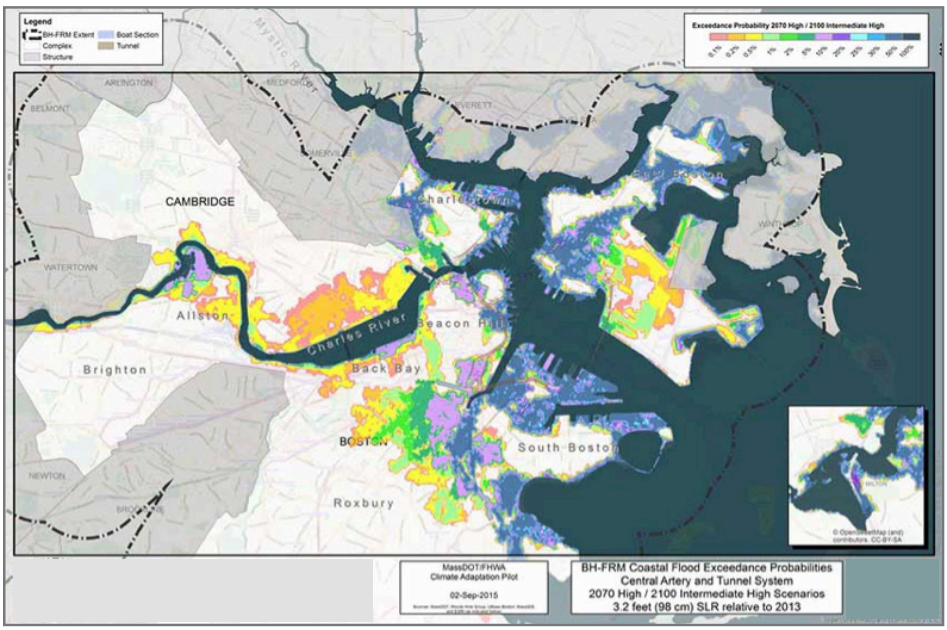
CAMPO developed risk summary fact sheets for each asset studied that explain the extreme weather risks it faces. This is an example Risk Summa ry Matrix for SH 71E at SH 21. Flooding and drought present the greatest risks to this asset, while wildfire and extreme heat present moderate risks. Though flooding is projected to occur less often than drought, it would have greater consequences for the asset. (Source: CAMPO)

[52] One such analysis method is the Monte Carlo method, which is a type of simulation that explicitly and quantitatively represents uncertainty by repeating an analysis using a large number of different values for its critical parameters obtained by drawing repeatedly from their underlying probability distributions. By doing so, it generates a probability distribution of possible outcomes that incorporates the combined uncertainty surrounding each of these parameters.

Examples: Considering Risk

- **MassDOT** created the hydrodynamic Boston Harbor Flood Risk Model (BH-FRM) to identify risk and depth of water resulting from storm surge-induced coastal flooding in the city of Boston under current and future sea level rise and storm surge. The BH-FRM employed a Monte Carlo method to explicitly and quantitatively represent uncertainty of the anticipated coastal storm processes and their potential impacts from storm surge flooding. Using the BH-FRM, the MassDOT team modeled a statistically robust sample of storms under different climatic circumstances to determine the probability of flooding throughout the Boston Harbor region. For each of the four time horizons studied—2013, 2030, 2070, and 2100—the assessment team generated Coastal Flood Exceedance Probability Maps, showing the likelihood that a location within the BH-FRM domain will flood by 2 or more inches of water encroaching on the land surface at a particular location in any given year. Exceedance probabilities range from 0.1 percent (probability associated with the 1000-year water surface elevation) to 100 percent (probability associated with the highest annual tide).
- **CAMPO** evaluated the risks of flooding, drought, heat, wildfire, and extreme cold on nine critical transportation assets. CAMPO used an indicator-based approach to calculate risk; they used the VAST exposure rating to determine likelihood of exposure and the VAST sensitivity and adaptive capacity ratings to determine the consequence of exposure. The results were then vetted with expert focus groups and adjusted as need. CAMPO summarized the results in risk matrices for each asset (see Figure 16).
- As part of the FHWA collaboration with the Netherlands, the RWS research team used the following criteria and weighting for classifying the consequences of climate change impacts for the A58 highway on a scale of one to four: safety (22 percent), availability (19 percent), environment (17 percent), effects for surrounding road network (13 percent), direct costs (12 percent), effects on maintenance (10 percent), and reputation (7 percent). For the estimation of likelihood, a score of 1 signified very seldom, or less than once every 250 years; 2 signified once every 50 to 250 years; 3 indicated every 10 to 50 years; and 4 indicated often, or more than once every 10 years. The team first scored the current likelihood of these risks. The

Figure 17. Boston Central Artery/Tunnel Coastal Flood Exceedance Probability Map



MassDOT developed Coastal Flood Exceedance Probability maps for each of the four time periods studied. This map shows an intermediate scenario of coastal flooding of the Central Artery/Tunnel system in 2070 with 3.2 feet (1 meter) of sea level rise relative to 2013. Included is 2.5 inches (6 centimeters) of land subsidence. The majority of flood areas range from 1 percent to 50 percent probability of flooding. (Source: MassDOT)

Using the BH-FRM, the MassDOT team modeled a statistically robust sample of storms under different climatic circumstances to determine the probability of flooding throughout the Boston Harbor region.

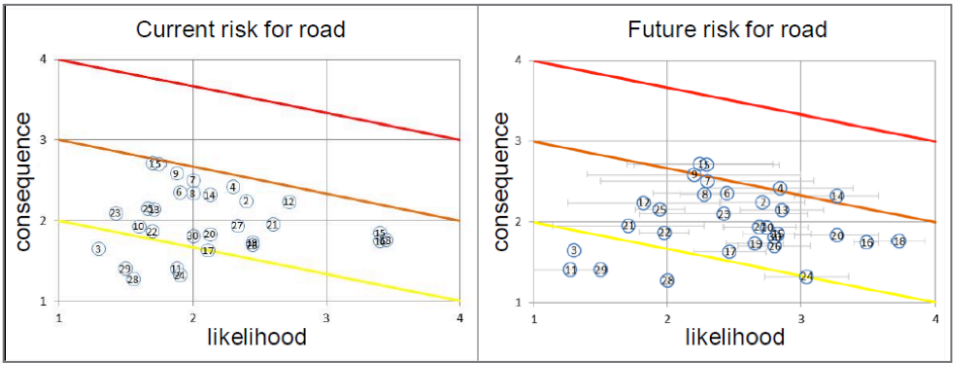
Examples: Considering Risk (Continued)

RWS team then adjusted the likelihoods upwards for future risks based on precipitation intensity and frequency projections developed by the Netherlands meteorological institute for climate change scenarios.

The highest risks for A58 are listed below in order from low risk to high risk; the numbers in parentheses correspond to the numbers in the matrices:

- Flooding of road at creek crossings (1)
- Pluvial flooding (road flooding as a result of heavy rainfall–surface runoff, increase in groundwater level, puddle forming) (2)
- Erosion of roads due to undersize culverts (4)
- Erosion/loss of bearing capacity in the road sub-base due to prolonged water alongside road (5)
- Landslide/road subsidence of embankment in periods of extreme precipitation (6)
- Loss of driving safety due to restricted visibility during snow or showers, including spray (16)
- Driver safety due to water on roads (hydroplaning when water film is thicker than 3 mm) (18)
- Flooding of underpasses (31)

Figure 18: A58 Risk Matrices for Current and Future Conditions



RWS developed risk matrices for a segment of the A58 highway based on the consequence of 30 different climate impacts on the road as well as current and future likelihood of those impacts. (Source: RWS/Delatres).

Resources for Considering Risk

Video: Building a Risk Management Response to Climate Change, FHWA, 2015. In this short video, Klaus Jacob and Cynthia Rosenzweig of the New York City Panel on Climate Change describe New York's risk-based approach to addressing vulnerability, including the use of flexible adaptation pathways and periodic reassessment to realign objectives with new information.

5 Identifying, Analyzing, and Prioritizing Adaptation Options

After identifying vulnerabilities through a system-level analysis, an engineering-based assessment, or a hybrid of the two, practitioners can identify adaptation options to address vulnerabilities. Depending on the scope and results of the assessment, the list of vulnerable assets could be long, and thus it may be too time consuming to adequately identify adaptation solutions for each vulnerable asset. Practitioners will likely want to focus on developing a list of fewer but more detailed adaptation strategies for a subset of assets or vulnerabilities.

Many transportation agencies choose to focus adaptation efforts on those assets identified as most at-risk (i.e., having high likelihood of and consequence to climate impacts). Other options for limiting adaptation efforts may include: focusing on vulnerable assets that are already included in transportation plans or programs for replacement or expansion; studying a range of asset types or identified vulnerabilities; selecting one asset per participating jurisdiction; or selecting assets where adaptation solutions are likely feasible.

Adaptation solutions can be natural, structural, or policy-based and can range from site-specific to regional. Strategies may include:

- Engineer new assets to withstand environmental conditions anticipated in the future (e.g., use construction materials better suited to higher heat days);
- Retrofit existing assets to accommodate impacts (e.g., add barriers to prevent water incursion into tunnels, harden roadway embankments);
- Increase redundancy of the system to ensure transportation services provided by infrastructure can be supplied by other means/alternatives (e.g., build alternative access routes at higher elevations);
- Relocate assets to avoid damage;
- Institute intensive maintenance schedules (e.g., more frequent cleaning of drains);
- Incorporate findings into asset management plans and systems;
- Integrate findings into systems planning (e.g., site new facilities outside of expanded floodplains where their potential for climate-related damage is reduced); and
- Improve operations plans for weather emergencies.

Many possible adaptation options can be implemented even in the face of uncertainty about future climate impacts. Flexible options–i.e., those that can be modified as conditions change or as new data becomes available–can help address this uncertainty. Agencies should consider developing climate variable thresholds that trigger specific actions when reached (e.g., a commitment to build a flood barrier if the relative sea level rise for the region exceeds a certain threshold). Keep in mind that adapting certain assets may increase or reduce the adaptability of other assets.

After developing potential adaptation options to address the vulnerabilities identified in the assessment, practitioners can use a variety of methods to select adaptation options to implement. The following sections provide information on two of these methods: multi-criteria analysis and economic analysis.

USING MULTI-CRITERIA ANALYSIS TO EVALUATE ADAPTATION OPTIONS

Multi-criteria analysis (MCA) involves comparing adaptation options across a range of qualitative and quantitative criteria. One benefit of MCA is that it allows practitioners to consider aspects that cannot easily be quantified or put into monetary terms, such as impacts to the environment or communities.

Potential criteria to consider in the analysis include the adaptation option's:

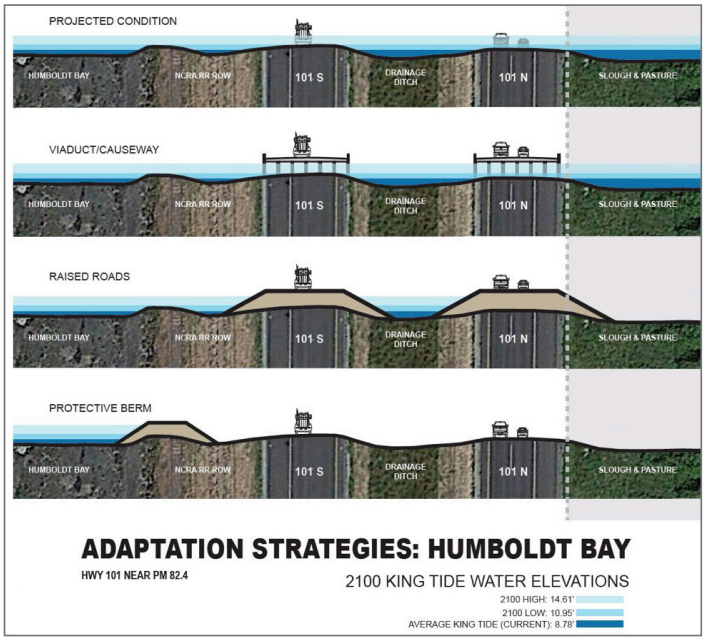
- Effectiveness in responding to climate stressors across a range of climate scenarios
- Capital and life-cycle costs
- Environmental impacts
- Technical feasibility

- Permitting constraints
- Public acceptance
- Environmental justice impacts
- Scale or impact of the response

Evaluating each potential adaptation option, including a "no action" scenario, across the selected criteria will allow practitioners to understand the strengths and weaknesses of each option. Agencies can prioritize the criteria most important to them by giving these criteria a higher weight in the analysis or by eliminating options that do not score well on these criteria.

In analyzing adaptation options, it is important to engage stakeholders as adaptation strategies are more likely to be successful if developed through a participatory process involving internal and external partners. Stakeholders, including the public, can be involved in selecting the criteria, determining the weightings for each criteria, and rating the adaptation options.

Figure 19: Cross-Section of Adaptation Options for Humboldt Bay, California



Caltrans considered eight adaptation options to address sea level rise along Highway 101 on Humboldt Bay. These strategies include the addition of a viaduct/causeway with raised roads and with a protected berm. (Source: Caltrans, District 1)

Engage Stakeholders on Selecting and Implementing Adaptation Options

Engaging internal and external stakeholders in adaptation planning is critical for the successful integration of such efforts into transportation decisionmaking processes (See section 7). Successfully engaging internal staff requires listening and incorporating their feedback and perspectives. If these staff members are engaged, they may be more willing to take ownership of or provide valuable leadership on ensuring climate change resilience is incorporated into work processes and programs. External stakeholders, including other agencies, community groups, and the public at large, who may have innovative ideas for adaptation strategies and may be able to help prioritize adaptation options and strategize around how to implement them. Getting public buy-in on vulnerabilities and adaptation strategies can help ensure better, more sustainable implementation.

Engaging stakeholders and the public also involves effectively communicating the process and results of the vulnerability assessment. During the pilot studies, transportation agencies successfully communicated adaptation issues and concepts to stakeholders by framing them as follows:

- Adaptation is responsible risk management and more holistic planning.
- Adaptation saves money. Preventing impacts is almost always less expensive than cleaning up and rebuilding after an extreme weather event.
- Past events, such as severe flooding event or a heat wave, help communicate what climate projections tangibly mean for communities.
- Impacts and adaptation issues can be referred to as "extreme events," "all-hazard planning," and "resilience."

In analyzing adaptation options, it is important to engage stakeholders as adaptation strategies are more likely to be successful if developed through a participatory process involving internal and external partners.

Examples: Using Multi-Criteria Analysis to Evaluate Adaptation Options

- **Caltrans District 1** evaluated adaptation options using criteria such as cost, usable life, level of performance, flexibility of design (i.e., the ability of the adaptation options to be modified to provide a higher level of protection against impacts or updated as new data models for climate change are developed), and social and environmental considerations. The agency weighted these criteria based on input from stakeholders and public meetings to reflect local priorities and values. The criteria methodology was formalized into a tool to assist planners with the evaluation and selection of adaptation options.
- The **MTC project** team in the San Francisco Bay area developed a compendium of 124 adaptation strategies to directly address the governance, information, physical, and functional vulnerabilities identified in the vulnerability assessment. The team used a screening exercise, followed by a qualitative assessment, to select adaptation strategies for further development (see Figure 19). 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. MTC found that the qualitative assessment was a good way to evaluate the performance of strategies, but the project team ultimately used their local knowledge and expertise to select a final set of balanced strategies.

Resources for Identifying, Analyzing and Prioritizing Adaptation Options

Transportation Engineering Approaches to Climate Resiliency (TEACR) Study, FHWA, 2017. This report provides lessons learned for a range of engineering disciplines when considering climate change and extreme weather events in engineering and also discusses analytical processes for addressing climate change and extreme weather events in project level assessments. This work was based on multiple engineering-informed adaptation studies that sought to address climate change concerns, including nine that were conducted as part of this project with a range of State partners.

Post Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, FHWA, 2017. This final report from the study includes information on damage and disruption from Hurricane Sandy on the region's transportation systems, along with that of Hurricane Irene, Tropical Storm Lee, and Halloween Nor'easter Alfred. The report also includes engineering-informed assessments of climate vulnerabilities and risks and evaluation of potential adaptation strategies for a selection of transportation facilities–roads, bridges, tunnels, rail, and ports–that can be considered for these and similar facilities.

ROADAPT Guideline part E: Selection of adaptation measures. Conference of European Directors of Roads, 2015. Provides process for selecting adaptation options and a matrix of measures by category (hydraulic capacity of culverts, hydraulic capacity of road drainage systems, stability of road embankments after flooding, landslides, tunnel uplift, embankment erosion, heat stress on pavements, spring thaw pavement deterioration, and traffic management in situations with operation restrictions). These guidelines include a companion database of adaptation strategies.

International Climate Change Adaptation Framework for Road Infrastructure. World Road Association, 2015. This framework includes resources and instructions to help transportation and road decisionmakers cope with the negative effects of climate change and manage them systematically and efficiently. This document guides road authorities through the process of increasing the resilience of their networks and assets through four stages. Stage 3, Developing and Selecting Adaptation Responses and Strategies, includes information on how to conduct a multi-criteria analysis.

USING ECONOMIC ANALYSIS TO EVALUATE ALTERNATIVE ADAPTATION OPTIONS

Economic analysis, a useful tool to evaluate public investments, can help agencies evaluate and prioritize adaptation options by clarifying the potential long-term costs and benefits of alternative adaptation strategies. An economic analysis can measure those costs and benefits in terms that allow the options to be compared individually, as well as with current policies and practices. It offers a systematic and transparent framework to organize information on asset vulnerability, compare alternative approaches for reducing vulnerability, evaluate benefits and costs of each approach, and inform decisions on which alternative or strategy to pursue.

The next two sections focus on broad issues pertaining to economic analyses: defining the scope of analyses and identifying costs and benefits. Section 6.2.3 discusses two primary types of economic analysis: Economic Impact Analysis (EIA) and Benefit-Cost Analysis (BCA). At the broadest geographic scale, EIA can provide policymakers with a high-level look at how planning policies and decisions that address climate resiliency may impact the economy at a regional or statewide level. BCA can help agencies compare competing design options that reduce the vulnerability of broad classes of transportation infrastructure–bridges or airports, for example–to mitigate disruptions or damage caused by more frequent climate-related events. More specifically, it can help inform localized transportation decisions, such as designing and locating individual facilities to reduce their exposure or improve their ability to withstand extreme weather impacts. Adaptation strategies often come at an initial construction cost premium. Economic analysis helps decisionmakers evaluate and compare the long-term benefits and costs of each strategy as well as how such benefits and costs compare to existing policies.

Scope of an Economic Analysis

An economic analysis needs to be tailored to suit the decision it is intended to inform. The detail and reliability of climate projections, the level of resources available to support economic analysis, and the appropriate time horizon to use will all influence the scope of the economic analysis. More comprehensive assessment of economic impacts will often be possible for adaptation measures that involve individual transportation assets, since the detailed information necessary to evaluate the performance of specific infrastructure assets under alternative adaptation measures will often be available. In contrast, adaptation options associated with reducing the vulnerability of entire regional transportation networks are likely to encompass larger geographic areas containing numerous individual assets, so economic analysis of these measures often relies on more aggregate descriptions of the impacts of such strategies on network performance.

The level of detail used to analyze costs and benefits of adaptation options will necessarily be scaled to the "granularity" of climate projections and estimates of resulting infrastructure damages developed as part of the vulnerability assessments. The level of detail used in vulnerability assessments necessarily limits the precision with which potential damages to infrastructure (e.g., the expected value of damages at different flooding levels) and the economic benefits of alternative adaptation measures can be estimated. The appropriate level of detail will also be limited by the time and resources available to estimate benefits and costs, as well as on the number of adaptation options being evaluated.

The time horizon used in economic analysis will depend on timeframes of the climate projections used in the study. The inherently long-term nature of climate change and its gradual effects on the frequency of extreme weather events means that the time horizon necessary to capture the benefits and costs of alternative adaptation strategies is likely to exceed the usual analysis period for transportation infrastructure investments. A good rule-of-thumb for analyzing roadway investments is the service life of the asset. The analysis should consider a range of alternatives, each tied to the probability of the climate impact (e.g., frequency of severe weather events). The outcome of the analysis should provide a distribution of net-benefits and probabilities of the realization of those net-benefits.

Costs and Benefits to Consider

Economic analysis should ideally consider both direct costs and benefits of the adaptation option to transportation agencies, travelers, households, and businesses, as well as broader socio-economic and environmental impacts.

Direct costs of alternative adaptation options include initial costs to construct or retrofit facilities in ways that reduce their vulnerability. Although the implementation of alternative adaptation options may produce lower long-term costs, these options often come at an initial construction cost premium when compared to traditional approaches.

Direct benefits to transportation agencies include avoided maintenance and construction costs and time required to repair, or in extreme cases, to reconstruct damaged facilities. Other consequences—such as disruptions of transportation activity and resulting delays to travelers and freight shipments—are also potentially significant and should ideally be incorporated in economic evaluation of alternative adaptation measures. Measures that improve the resilience of critical transportation facilities or networks can reduce the frequency or severity of these potential disruptions. The economic value of reduced delays to travelers and more reliable freight shipments should be included among the direct benefits.

Indirect effects of improving the resilience of transportation infrastructure can also be widespread and significant, and economic analysis should not overlook these indirect impacts. Environmental impacts (e.g., environmental costs and benefits) and social impacts (e.g., human health and well-being costs and benefits) represent a broad and important category of indirect effects that may result from redesigning or relocating transportation facilities or investing in protective features to improve resilience. Although they can be difficult to value in economic terms, the range of environmental and social impacts for which useful dollar-denominated measures are available continues to expand. For example, changes in the severity of air and water pollution, emissions of GHGs that contribute to climate change, and access to recreational amenities are now routinely valued in the economic analyses of government regulations and proposed infrastructure investments. Other environmental impacts such as threats to wildlife habitat or species diversity remain challenging to value economically. Where these impacts occur, it is nevertheless important to quantify their magnitude using physical measures, or by qualitatively describing their nature and likely extent. While the availability of information or resources will limit the scope of indirect benefits that can be considered in an economic analysis, it is important not to impose arbitrary or unnecessary limitations on which indirect effects to include.

Another indirect effect of climate and extreme weather impacts on the transportation system is the disruption it can have on local economic activity. For example, temporary closure of critical facilities or restrictions on their capacity may impair local retail activity or disrupt inter-regional freight flows. These impacts may be partly offset by shifts in retail activity to competing locations or rerouting of freight shipments. Measuring the extent and duration of any net reduction region-wide economic activity or increase in shipping costs that result from such disruptions is inherently difficult. Nevertheless, mitigating these potentially costly impacts can be another important source of indirect benefits of improving climate resiliency.

Types of Economic Analysis

Different types of economic analysis can be used to evaluate the costs and benefits of alternative adaptation options.

Economic Impact Analysis (EIA) seeks to inform high level decisionmakers such as elected officials on the impacts of transportation policies or investments on the local, regional, or national economy. These impacts typically take the form of changes in local employment, wage rates, retail sales or other measures of economic activity, and freight shipments originating in or destined for the region where the analysis is focused.

Because of its limited geographic scope, an EIA can be useful for identifying localities, particular economic sectors, or segments of the population and workforce that are particularly affected by measures to improve the local transportation system's climate resilience. This feature makes it useful for comparing locations, designs, or protective measures for specific infrastructure assets that serve primarily local or intra-regional transportation activity, since both costs and benefits of such measures will often be concentrated within the area where such facilities are located. However, this localized focus may hamper its usefulness for comparing alternative measures whose economic impacts span larger or different geographic scales, such as adding capacity or redundancy throughout a regional network or imposing region-wide design standards for transportation facilities that reduce their vulnerability to disruption or damage from climate events.

Benefit Cost Analysis (BCA) evaluates the benefits and costs of adaptation options to include justification for the options in terms of benefits to travelers and businesses and identifies the best timing for implementation by quantifying the level of benefits under different scenarios. Direct benefits can include the value of reduced delays to travelers and shippers, reductions in crashes, improved emergency responder access, less damage to or loss of freight shipments, and faster restoration of capacity. A BCA can also be used to analyze the indirect benefits of adaptation options, such as those related to water quality, habitat and species protection, erosion control, and recreational opportunities.

Several guidance documents provide detail on how to include the broad range of economic costs and benefits that are often analyzed in a BCA. For example, the USDOT's *BCA Resource Guide*[53] provides information on converting outcomes such as improvements in service reliability, safety, or species protection to economic benefits that can be measured as dollar values. The American Association of State Highway and Transportation Officials (AASHTO) also provides guidance and spreadsheets for computing these values in their *User and Non-User Benefit Analysis for Highways.*[54]

It is important to note that both an EIA and BCA can be used to measure the benefits of adaptation strategies, but these benefits must then be compared to the outcomes of existing practice and plans to understand their effectiveness. The economic value of benefits compared to a "business-as-usual" scenario represent the appropriate measure of benefits from adaptation strategies.

[53] "TIGER Benefit-Cost Analysis (BCA) Resource Guide." Transportation.gov. March 27, 2015. Accessed June 23, 2017. https://www.transportation.gov/sites/dot.gov/files/docs/Tiger_Benefit-Cost_Analysis_%28BCA%29_Resource_Guide_1.pdf.

[54] "User and Non-User Benefit Analysis for Highways, 3rd Edition." AASHTO Bookstore. 2010. Accessed June 23, 2017. https://bookstore.transportation.org/collection_detail.aspx?ID=65.

Life-cycle cost analysis (LCCA), a subset of BCA, is an approach commonly used to evaluate the differential costs of alternative designs or initial investment levels for transportation infrastructure. An LCCA focuses primarily on identifying the long-term costs to transportation agencies of different alternatives over the complete time horizon that captures a major reconstruction. This analysis is typically less intensive than a full BCA since the options and anticipated performance being compared have been identified. LCCA typically examines the direct cost impacts on transportation agencies of adopting different designs or varying capital investment levels, highlighting tradeoffs among initial construction outlays, recurring operating and maintenance expenses, periodic repairs, and reconstruction costs over an asset's expected lifetime. Costs occurring in different future time periods are discounted to their present values (i.e., usually as of the date of the analysis itself) in order to express the effects of design changes or investment alternatives on each cost category in comparable terms. This enables analysts to identify alternatives that reduce or minimize long-term costs incurred by a transportation agency over the analysis time horizon. An LCCA does not consider the external cost and benefits of adaptation options, i.e., the impacts to travelers, businesses, and/or the environment.

In the climate context, an LCCA would first examine the effects of strategies to reduce asset vulnerability on initial investment costs, including engineering, land acquisition, site preparation, and construction costs. It would then focus on the performance of alternative designs in terms of the likely frequency and scale of repair or reconstruction costs that would be required over the analysis time horizon. Measures that improve an asset's or network's climate resilience will typically entail higher initial investment costs, but would normally be expected to reduce future costs for necessary repairs, retrofitting, or reconstruction over its expected lifetime. More desirable or preferred alternatives can be identified by comparing the present values of each alternative's discounted life-cycle costs, including each of these categories. LCCA can also examine the sensitivity of these comparisons to alternative assumptions about the frequency and severity of potentially damaging climate events and the discount rate applied to future costs.

Incorporating Risk into Economic Analysis

When analyzing measures to reduce climate vulnerability, it is important for the study team to remember that weather-related events and their consequences are inherently uncertain. The risks of potential disruption or damage to transportation networks reflect the expected frequency, location, and severity of future weather events as well as their likely impacts on the condition and performance of network infrastructure (see section 5.3 for more information on considering risk). Economic analyses need to incorporate these risks and their potential consequences in order to be useful to transportation planners and public officials.

Conducting an economic analysis to evaluate adaptation options requires an understanding of both the expected frequency of different levels of climate impacts, and the economic damages that

Choice of Discount Rates

Discounting is an economic method of determining the time value or opportunity cost of an investment, generally equal to the economic return that could be earned on the invested resources in their next best alternative use. Economic analyses use discount rates to convert anticipated future costs and benefits to present dollar values so different alternatives and time horizons can be directly compared. The discount rate used in the economic analysis is particular important when evaluating and comparing adaptation options, as the associated benefits (or avoided costs) are likely not realized for many decades.

The choice of discount rate can have a significant impact on the apparent project cost effectiveness of adaptation options and therefore on decisionmaking. For adaptation options, which typically have the associated costs concentrated in the early years and the benefits following in later periods, raising the discount rate tends to artificially lower the net present value of the resilience strategy and overly ignore the benefits of resilient infrastructure to future generations. In contrast, low or zero discount rates tend to increase the net present value of resilience strategies in relation to business as usual.

There is no consensus on the appropriate discount rate to use for resilience strategies. As a best practice, study teams may choose to explore the sensitivity of economic analysis findings to different discount rates. Alternatively, study teams may apply a non-constant discount rate over the forecast horizon. In the **Post Hurricane Sandy Transportation Resilience Study,** the project team applied a decreasing discount rate to calculate the effect that disruption of a specific transportation asset would have on the regional economy over the forecast horizon. The analysis assumed a 3% real discount rate from 2010 through 2034, 2% for 2035–2084, and 1% for 2085–2100.

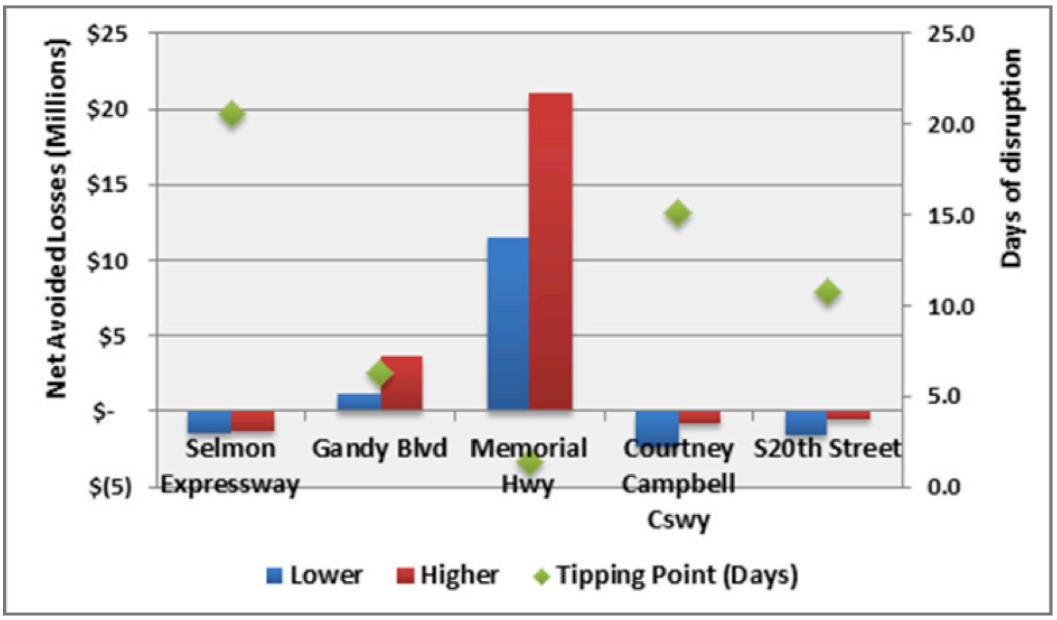
different stressor levels are likely to inflict on specific infrastructure assets. This includes the anticipated frequencies of events such as extreme precipitation, sea level rise, or coastal storm surges, as well as the range of potential severity of each event and the estimated cost of the resulting damages to specific assets, expressed as dollar figures. For evaluations using a longer time horizon, it will often be important to anticipate how these risks are likely to evolve over the future in response to changes in the global climate.

With this information, analysts can use Monte Carlo-type simulation methods to develop risk profiles of climate-related economic impacts such as service interruptions and delays, temporary capacity reductions, or structural damages to transportation assets. These methods can also simulate how these damages are likely to vary in response to different adaptation options, such as changes in location, design, or other features. Using estimates of the costs of delays to travelers and shipments, for example, these profiles can be used to calculate the distributions of potential savings from alternative adaptation options. Simulated distributions of benefits of alternative climate adaptation measures can then be compared to their costs in order to evaluate and recommend alternatives.

In practice, such detailed information about climate projections or related damages may not be available. In most cases, practitioners can use available historical data and institutional knowledge to provide input and deploy resources. In cases where there is a lack of data or institutional knowledge, analysts will need to rely on simplified representations of risks and consequences from potential climate-related events to estimate benefits from adaptation strategies. Where only point estimates of the future probabilities or frequencies of climate events and their possible consequences are available, analysts will need to rely on probabilistic expected values of climate-related damages to summarize the range of possible outcomes.

Analysts can then examine how expected damages caused by extreme weather events are likely to be affected by different adaptation options, such as relocating or incorporating additional protective features in the design of infrastructure assets, or by investing in increased capacity and redundancy of transportation networks. Again, the economic benefits of each adaptation strategy are measured by the difference in the economic value of expected damages with that strategy in place and their expected value under a business-as-usual baseline. Expected benefits for alternative measures to improve climate resiliency can then be compared to their respective costs to assess the economic return each one offers.[55]

Figure 20. Estimated Net Benefits/Avoided Losses from a Category 3 Hurricane Storm Surge Scenario



The Hillsborough MPO pilot produced two summary variables that describe the relative cost-effectiveness of the adaptation strategy package proposed for each asset: estimated net benefits/avoided losses resulting from reductions in the duration of disruption; and the "tipping point" (the number of days of avoided disruption required for the strategy package to achieve cost neutrality). The metrics summarized above reflect a Category 3 hurricane storm surge scenario. (Source: Hillsborough MPO)

[55] A detailed Monte Carlo simulation and more simplified analysis using expected values of benefits from alternative climate mitigation strategies for a single infrastructure asset are available in: Comparison of Economic Analysis Methodologies and Assumptions: Dyke Bridge in Machias, Maine. Report. September 2016. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/dyke_bridge/index.cfm.

Examples: Using Economic Analysis to Choose Adaptation Options

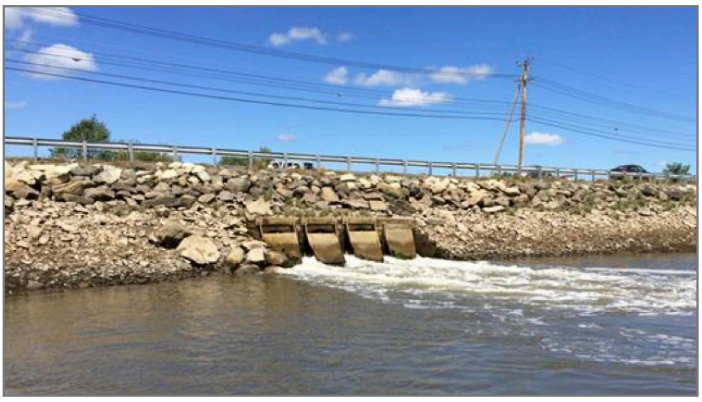
- **MaineDOT** analyzed the life-cycle costs for three vulnerable assets (a culvert and two bridges) to determine if it was more cost effective to replace the assets in-kind or design them to withstand certain levels of sea level rise. For each asset, MaineDOT bridge engineers developed adaptation design options for resilience up to 3.3 feet and 6 feet of sea level rise and corresponding cost estimates. The pilot team also worked with local engineers, maintenance crews, and maintenance records to create depth-damage functions, i.e., the estimated repair cost for an asset at each flood elevation, specific to each asset and their adaptation options. Although the structures were exposed to the same sea level rise scenarios, the most financially efficient design option varied by site.
- **Hillsborough MPO** estimated the general economic losses associated with disruption to various critical assets throughout Hillsborough County to identify the most cost-effective strategies to mitigate and manage risks of coastal and inland flooding. The project team used the regional travel demand model to estimate losses in regional mobility and other tools to estimate general economic losses associated with disruption of certain transportation facilities (See Figure 20). The project team developed a suite of adaptation strategies and estimated the marginal costs of each strategy package, assuming adaptation strategies were implemented during regular rehabilitation, reconstruction, and replacement activities.

  The Hillsborough MPO pilot produced two summary variables that describe the relative cost-effectiveness of the adaptation strategy package proposed for each asset: estimated net benefits/avoided losses resulting from reductions in the duration of disruption; and the "tipping point" (the number of days of avoided disruption required for the strategy package to achieve cost neutrality). The metrics summarized above reflect a Category 3 hurricane storm surge scenario.
- **MnDOT** conducted a facility-level vulnerability assessment for a large culvert in each of two studied districts. The assessment evaluated the performance of each culvert under three climate scenarios. The team designed one adaptation option for each of the three climate scenarios analyzed, and conducted a BCA to assess the physical damage and social costs (i.e., travel time delay costs and potential for motorist injury) of each adaptation option. Based on the results of the analysis, the team made recommendations on which adaptation option to pursue. For District 1, the MnDOT analyzed the performance of four replacement options: a base case replacement designed to today's standards, and three alternative options–a larger two-cell culvert and two different bridge design–each designed to perform optimally in the year 2100 under three different climate precipitation scenarios. If the social costs of detours and injuries are included in the cost estimates for the adaption options, then an expanded two-cell culvert designed to meet a low-precipitation scenario is the most cost-effective design under all future precipitation scenarios. However, when social costs are excluded, the most cost effective option varies between replacing the existing culvert with one designed to today's standards and replacing it with the expanded two-cell culvert.
- As part of its vulnerability assessment pilot, **Oregon DOT** conducted a BCA at two sites to compare the costs of repeated repairs (baseline scenario) with the construction and long-range maintenance costs of an adaptation option. The analysis also compared the benefits of each option in terms of time savings, reductions in vehicle operating cost, and safety improvement. For the Falcon Cove site, which is vulnerable to landslides, the adaptation option analyzed was to reconstruct the site with all-weather fill and replace the culvert with a newer, larger pipe at a more favorable grade. The economic analysis determined the benefits are not sufficient to justify the costs associated with the adaptation action.
- **New York State DOT (NYSDOT)** analyzed and developed a benefits valuation approach considering a range of social, economic, and environmental factors to help decisionmakers prioritize improved road-stream crossings and other infrastructure improvements. To address the difficulties associated with the valuation of environmental benefits, such as healthier fish and wildlife populations, improved habitats, decreased erosion, improved water quality, and enhanced river recreation, the agency developed a method to apply a multiplier to include environmental benefits in the overall benefits value for each culvert.

Examples: Using Economic Analysis to Choose Adaptation Options (Continued)

- As part of its TEACR Project engineering assessments, FHWA compared techniques for estimating the cumulative life-cycle damage costs of alternatives proposed for the Dyke Bridge in Machias, Maine (see Figure 21). The study showed that a scenario approach to climate change adaptation economic analyses is an effective way to consider the range of climate change uncertainty. FHWA calculated estimated project life cycle costs, benefit-cost ratios, and net present values for each adaptation option under each climate scenario, which provided decisionmakers with the information needed to make investment decisions. The study concluded that ideally an economic analysis should reveal the adaptation option that performs the best across the range of scenarios (the robust performer) or, if no such option exists, the option that has the lowest downside across the possible climate scenarios.

Figure 21. Dyke Bridge in Machias, Maine at Low Tide



FHWA considered climate change uncertainty using a scenario approach to climate adaptation economic analyses. (Source: FHWA)

Resources for Conducting an Economic Analysis

Synthesis of Approaches for Addressing Resilience in Project Development (Chapter 6), FHWA, 2017. This report summarizes a range of techniques and lessons learned on conducting economic analysis of adaptation measures based on pilots to help transportation agencies address changing climate conditions and extreme weather events at the asset level.

Comparison of Economic Analysis Methodologies and Assumptions, Dyke Bridge in Machias, Maine, FHWA, 2016. This is one of nine engineering case studies conducted under the TEACR Project. This case study focused on comparing the approaches and outcomes of two climate change adaptation economic assessments.

Benefit-Cost Analysis Guidance for TIGER Grant Applicants, USDOT. This document provides general information and guidance on conducting a BCA. The supplemental **Benefit-Cost Analysis (BCA) Resource Guide** provides technical information on monetizing benefits and costs, as well as guidance on methodology.

Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses–2016 Revision, USDOT, 2016. Agency guidance on the value of a statistical life to use when assessing the benefits of preventing fatalities. The guidance also establishes policies for assigning comparable values to prevention of injuries.

Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, USDOT, 2015. Outlines procedures to determine the value of travel time savings to use in agency benefit-cost or cost-effective analysis of regulatory actions or investments.

Guidelines for Preparing Economic Analyses, U.S. Environmental Protection Agency, 2010. The guidelines provide a scientific framework and guidance on analyzing the benefits, costs, and economic impacts of regulations and policies, including assessing the distribution of costs and benefits among various segments of the population.

ROADAPT Guideline D: Socio-economic impacts analysis, Conference of European Road Directors, 2015. Part of the overall ROADAPT guidelines, this report contains details on how to perform a socio-economic impact assessment of the consequences of weather events and the impact of adaptation strategies.

6 Incorporating Assessment Results in Decisionmaking

Integrating the results of a vulnerability assessment into existing transportation programs and processes ensures that study results are used in practice. While information developed from the vulnerability assessment should be used to satisfy the study objectives, the results may also be useful in ways not initially anticipated.

This section outlines strategies to effectively incorporate results into transportation planning and project prioritization, environmental review, design, operations and maintenance, and asset management. The section concludes with steps agencies can take to monitor adaptation strategies and revisit study assumptions and data as time goes on.

INCORPORATING RESULTS INTO TRANSPORTATION PLANNING

Statewide and regional transportation planners play a role in enhancing the climate resilience of existing and future transportation projects. The transportation planning process provides a key opportunity for transportation agencies to proactively identify projects and strategies that address risk and promote resilience at the systems level.

Climate resilience should be considered early during decisionmaking at the system-wide level, when options and priorities are considered for transportation investments. The results of a vulnerability assessment provide agencies with useful information to screen projects during the planning phase to avoid making investments in particularly vulnerable areas or to build resilience into project design. Agencies can also use the findings from a vulnerability assessment to inform project prioritization by highlighting projects that can improve the resilience of the transportation system (i.e., identify projects that provide necessary redundancy in a vulnerable area). In general, activities to plan, design, and construct highways to adapt to current and future climate change and extreme weather events are eligible for reimbursement under the Federal-aid program and for funding under the Federal Lands program.[56]

Taking resilience into account during the transportation planning process is not only good practice, it is part of the Federal transportation planning requirements. The FAST Act, signed into law in December 2015, requires transportation agencies to take resilience into consideration during transportation planning processes. Following passage of the FAST Act, FHWA and the Federal Transit Administration (FTA) updated the metropolitan and statewide transportation planning regulations to reflect these new requirements (23 CFR 450.200 and 23 CFR 450.300) processes. The final planning rule included a new planning factor on improving resiliency and reliability of the transportation system. The final rule also added a requirement for MPOs to coordinate with officials responsible for natural disaster risk reduction when developing a metropolitan transportation plan and the TIP, and adds a requirement to assess capital investment and other strategies that reduce the vulnerability of the existing transportation infrastructure to natural disasters (Section 450.324(f)(7)). Agencies can use the information from and results of a vulnerability assessment to meet these planning requirements.

Climate Change Impacts on Environmental Justice Communities

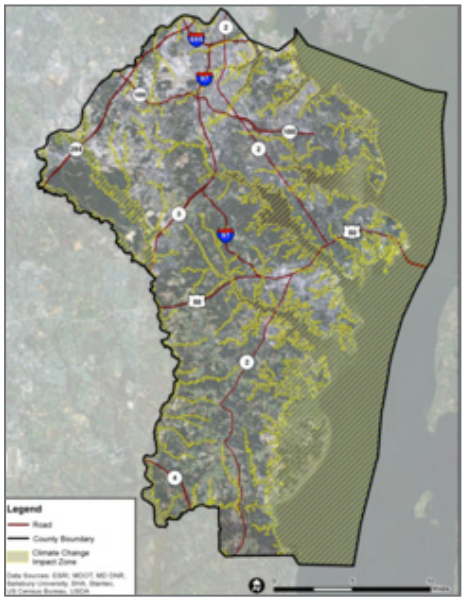
While climate-related transportation damages and disruptions affect all commuities, environmental justice (EJ) communities are particularly impacted. Transportation agencies at the Federal, State, and local levels can reduce negative impacts of climate change on EJ communities through stakeholder inclusion, proactive planning, and risk mapping. Inclusive stakeholder engagement in long-range transportation planning and throughout the transportation project development process provides a forum in which citizens and entities such as emergency responders, healthcare industries, paratransit companies, utilities, governments, and businesses can more tangibly understand and prepare response plans to address climate change impacts on transportation infrastructure in EJ communities.

[56] FHWA, September 12, 2002. Eligibility of Activities To Adapt To Climate Change and Extreme Weather Events Under the Federal-Aid and Federal Lands Highway Program. Available at **https://www.fhwa.dot.gov/federalaid/120924.cfm**

Examples: Incorporating Results into Transportation Planning

- The **Hillsborough MPO** incorporated the results from its vulnerability assessment into its **2040 Long Range Transportation Plan.** One of the objectives of the plan is to increase the security and resiliency of the multimodal transportation system. The performance measure associated with this objective is the recovery time and economic impact of a major storm. The security chapter of the plan integrates the findings from the vulnerability assessment to highlight elements of the transportation network that are vulnerable to flooding. As part of the long-range planning process, the MPO developed and evaluated three risk management investment scenarios—a base case, a medium investment scenario, and a high investment scenario—and evaluated the degree to which the investment mitigated potential impacts. The MPO evaluated how much disruption and economic loss the residents and businesses of Hillsborough County will endure when storms and flooding impact the regions for different levels of investment in adaptation and mitigation. For instance, the MPO found that a suite of adaptation actions would cost $31M, but avoid $265M in losses.
- CAMPO integrated the results of its vulnerability assessment into its **2040 Regional Transportation Plan.** The plan summarizes the climate-related risks to the region's transportation system and identifies potential measures that the CAMPO region can implement to proactively increase the transportation system's climate resiliency. The plan also includes an action plan intended to bring elements of the plan to life. One of the priority action items is to increase extreme weather resiliency by evaluating the adequacy of potential wildfire and flood evacuation routes; identifying opportunities to increase system redundancy and alternate routes; and advancing best practices in addressing drought-related impacts on the transportation system.
- MassDOT developed the MassDOT Project Planning System (MaPPS), a web-based GIS application designed to improve the quality of project scopes using location-based criteria. The tool allows users to access over 30 location-based transportation, safety, environmental, and vulnerability data layers, including the inventory of flood prone areas. Through the tool, project planners are made aware of vulnerability issues and potential adaptation solutions early in the project planning process.
- **Maryland SHA** is using the results of its vulnerability assessment to delineate coastal locations vulnerable to flooding (see Figure 22). This data is intended to help MDSHA screen new project plans and designs for resilience to future climate impacts. The SHA will use the screening mechanism to inform its Highway Needs Inventory, a planning document that lists major capital construction projects.

Figure 22: Climate Change Impact Zone for Anne Arundel County, Maryland



The shaded yellow lines in this image depict climate change impact zones the Maryland SHA mapped along with roads (in red). (Source: Maryland SHA)

Resources for Incorporating Results into Transportation Planning

Resilience and Transportation Planning, FHWA, 2017. This fact sheet outlines updates to the metropolitan and statewide transportation planning regulations to reflect new FAST Act requirements to address resilience and natural disaster risks.

Addressing Climate Change Adaptation in Regional Transportation Plans: A Guide for California MPOs and RTPAs, Caltrans, 2013. This guide is intended to be a resource to support MPOs and regional transportation planning agencies (RTPAs) in incorporating climate change impacts into their decisionmaking and planning processes. The guide provides MPOs and RTPAs with: (1) background information on climate adaptation; (2) recommended data and information to assist in incorporating climate considerations into regional planning; and (3) a step-by-step process for integrating climate risks into plans.

INCORPORATING RESULTS INTO PROJECT DEVELOPMENT AND ENVIRONMENTAL REVIEW

It is important to consider climate change impacts and adaptation early in the project development process to ensure that climate resilience is incorporated into the project design to the extent possible and appropriate.

Transportation agencies can use the data gathered from and the results of vulnerability assessments to inform their analysis of climate change impacts in the environmental review process required under the National Environmental Policy Act (NEPA). Through the NEPA process, agencies could consider the potential impacts of climate change on a proposed action or the potential impacts of a proposed action on an environment vulnerable to climate change. For example, if a transportation agency plans to build a road on a barrier island, it should consider the effects of sea level rise and flooding on the proposed road, as well as whether constructing the road will exacerbate erosion and increase flood risks.

Vulnerability assessments, and more specifically engineering-informed adaptation studies, can provide a source of location-specific data and information on climate change impacts that agencies can incorporate into their NEPA analysis. The results of such studies can help agencies understand how climate change is likely to affect the proposed action, including:

- Whether the proposed action is in a location vulnerable to climate change;
- Which climate impacts the proposed action may be vulnerable to (e.g., inland flooding, extreme heat, storm surge, etc.);
- How the proposed action may exacerbate existing vulnerabilities of its location and the systems with which it interacts.

As described in previous sections, an agency may also be able to use the results of a vulnerability assessment to develop and select project alternatives that minimize vulnerabilities, or to develop adaptation strategies as mitigation measures or for inclusion in the proposed action.

Examples: Incorporating Results into Project Development and Environmental Review

- In its first pilot, WSDOT completed a statewide assessment of climate vulnerability of State-owned transportation assets. WSDOT incorporated the results of the assessment into its **Guidance for NEPA and SEPA Project-Level Climate Change Evaluations.** The guidance advises project teams to examine the results of the 2011 statewide assessment and the associated GIS data layers for information on the vulnerability and/or strengths of existing WSDOT facilities in the project area. WSDOT has published more than a dozen environmental documents that describe how the proposed project examined the results of the vulnerability assessment and what elements of the project improve resiliency.
- In the **2013 Final Environmental Impact Statement (FEIS)** for the St. Johns River Crossing, the Florida DOT and FHWA analyzed the proposed bridge for climate change impacts related to sea level rise and storm surge. They evaluated projected sea level and storm surge elevations against the vertical clearance and approach elevations for each proposed alternative. The analysis found that while storm surge impacts could increase slightly due to continued sea level rise, the vertical clearance and the approaches would be sufficient to protect against the potential for sea level rise. Because the projected increases in sea level and associated storm surge through 2100 are not expected to render any of the proposed bridge Build Alternatives dysfunctional, the FEIS did not recommend action to address sea level rise and storm surge.
- The Maryland SHA is using maps developed from their vulnerability assessment to screen for sea level rise impacts as part of their Programmatic Categorical Exclusion (PCE) reports. The PCE form asks if the project is within an area potentially affected by sea level change (based on 2050 and/or 2100 mean sea level and/or MHHW). If so, the form notes that the project must consider sea level change. The project lead is also asked to attach a Sea Level Change Map showing the project disturbance in relation to 2050 and 2100 mean sea level and MHHW.

Resources for Incorporating Results into Project Development and Environmental

Climate Change in NEPA Case Studies, FHWA. This series of case studies explores examples of how different projects have used their NEPA or other environmental reviews to plan for climate change impacts.

Synthesis of Approaches for Addressing Resilience in Project Development (Chapter 3), FHWA, 2017. This document provides a brief overview of where and how engineering-informed adaptation studies can be incorporated into the transportation project development process, including environmental review.

INCORPORATING RESULTS INTO PROJECT LEVEL DESIGN AND ENGINEERING

Transportation assets, such as roads and bridges, are built to withstand a range of environmental conditions for factors such as precipitation, flow, and temperature. The results of a vulnerability assessment can help transportation agencies identify assets, both planned and existing, for which climate vulnerability ought to be considered. This is particularly true for critical assets with long service lives.

How the results of a vulnerability assessment are used in engineering design depends largely on the level of detail of the analysis. As described in previous sections, developing climate projections and conducting vulnerability assessments may be performed at varying levels of detail, from a high-level screening to a detailed quantitative analysis. A system-level vulnerability assessment that considers regional changes in climate, or considers less-specific climate variables—such as average change in temperature or change in summer precipitation—may not be sufficiently detailed for design; further work would be needed to develop projected variables most relevant to the temporal and spatial scales used in design.

> The results of a vulnerability assessment can help transportation agencies identify assets, both planned and existing, for which climate vulnerability ought to be considered.

Vulnerability assessments conducted with more complex and detailed analysis can inform more specific engineering-based strategies and decisionmaking. Vulnerability assessments conducted at finer scales with detailed climate projections developed at the local level may provide the level of detail needed to inform engineering and design requirements for individual assets. For example, if a culvert has been designed in a watershed with a smaller time-to-peak value (e.g., <1 hour), and will be built in an area that is projected to incur additional episodes of extreme flooding, then engineers may opt to use climate model projections that may be more suitable to adjustment to finer temporal resolutions consistent with existing hydrologic models.

It is important to note that developing fine temporal scale climate projections may not be required depending on the size of the watershed being analyzed. For example, many design procedures require sub-daily resolution data, while available climate data generally is limited to 24-hr durations. Understanding the accuracy and purpose of transforming 24-hr duration projections into sub-daily estimates is an area of active research. In some cases, the use of daily resolution has proved acceptable. For example, the Iowa DOT found that using daily resolution for simulating peak flow statistics is acceptable for "big floods in big basins."[57]

To date, few transportation agencies in the United States have explicitly required design changes in anticipation of future climate change due, in part, to the lack of understanding of how best to incorporate projections into designs. This is particularly true in terms of developing projected values for extreme conditions. When future design inputs are developed using climate projections, there can be significant uncertainty and low scientific confidence in their projected magnitudes. On the other hand, some assets may already be sufficiently resilient to account for these future conditions.[58] To design specifically for future conditions, engineers may need to supplement their current design methods with procedures that incorporate future projections, such as those outlined in HEC-17.

There are various strategies for managing the uncertainty of climate change projections during development and design of transportation projects. A few include:

Flexible adaptation pathways. Practitioners can choose flexible strategies with timeframes that allow for changing course as new information emerges. The decision tree or pathway is mapped out over a timeline. Transfers from one adaptation strategy to another can be made at various points in time. As climate changes, some adaptation strategies have a limited window of effectiveness at which time they run into terminals or tipping points and new pathways must be followed. Each of the pathways can be rated qualitatively for cost effectiveness and possible unwanted side effects.

[57] Iowa Department of Transportation, March 2015, Iowa's Bridge and Highway Climate Change and Extreme Weather Vulnerability Assessment Pilot. http://www.fhwa.dot.gov/environment/climate_change/adaptation/resilience_pilots/2013–2015_pilots/iowa/final_report/index.cfm

[58] Assets may have inherently existing resilience due to the fact that design criteria are selected based on acceptable risk tolerance of the DOT, which tends to be appropriately conservative.

Using information on the direction of change. There is generally much greater certainty regarding the direction of change than the exact magnitude and timing of change. Knowledge of the expected direction of change (e.g., increasing or decreasing precipitation) is sufficient for some decisions. For instance, based on knowledge that debris and water flows are expected to increase as the climate changes on newer projects, Norway installed debris deflectors or screens to keep debris out of drainage systems and energy dissipaters in channels and culverts to reduce increased velocities.[59]

Sensitivity Analysis. Practitioners can use sensitivity analysis to estimate the impact that different future climate scenarios will have on the standard design versus a more robust design. For example, if the cost differential for using the next standard size larger for a certain material represents only a small increase in total costs, yet would perform better over a range of scenarios, the practitioner may decide the extra investment is warranted.

Contracting. In developing contracts for design or design-build, transportation agencies can require contractors to evaluate climate impacts and develop potential solutions.

Examples: Incorporating Results in Engineering Design

- As a result of its Disaster and Infrastructure Resiliency Planning Study, the Massachusetts Port Authority (Massport) developed and adopted design guidelines for flood resiliency (note: these guidelines apply to floodproofing buildings and equipment and not necessarily to roadways). In 2014, the Floodproofing Design Guide was incorporated into Massport's capital planning and real estate development processes to make its infrastructure and operations more resilient to anticipated flooding threats. These guidelines are for Massport staff, tenants, third party developers, design professionals and contractors to use during planning, design, and construction of new structures and additions, substantial repair, and improvement of existing structures, and retrofits of existing structures or facilities on Massport properties.
- The Port Authority of New York and New Jersey produced a memorandum that establishes project design evaluation criteria specifying that the "design of all new construction and major rehabilitation projects needed to be evaluated based on [specific] climate change variable impact." This memorandum specifies that designers consider the future change by the 2080s of an increase in the mean annual air temperature of 6°F, an increase of mean annual precipitation of 10 percent, a mean sea level elevation increase of 18 inches over current MHHW, and an increase of 18 inches over the current FEMA 100-year flood level plus one-foot criteria.
- After facing severe flooding and stream-related erosion impacts to road infrastructure during Hurricane Irene in 2011, the Vermont Agency of Transportation (VTrans) is employing a new approach for considering hydraulic capacity in design. VTrans is using hydrologic and hydraulic modeling and slope mapping to incorporate stream and slope stability into road design. Additionally, VTrans has redesigned their approach for repairing slope sections adjacent to rivers. Rather than placing stone to stabilize the slope, engineers are building the slope to match stable channel dimensions.
- The Connecticut DOT conducted hydrologic and hydraulic modeling to evaluate the vulnerability of 52 small bridge and culvert structures (6 to 20 feet in length) to inland flooding from extreme rainfall events. The evaluations showed that more than half of these assets were designed to withstand today's conditions, with only a portion of these assets identified as potentially requiring corrective action due to scour. The remaining assets were found to be hydraulically inadequate for today's conditions. These findings will be integrated into the bridge inventory to assist in outlining a plan/process for incorporating risk assessment into hydraulic design and asset management. Though this pilot did not consider future conditions, a key finding of this study is that the analysis does not recommend applying a universal adjustment to design flood frequencies due to the uncertainties of precipitation projections.
- The request for quotations (RFQ) for the A58 highway expansion project in the Netherlands included a section with requirements for the contractor related to climate resilience. That section requires the contractor to develop robust and flexible climate adaptation measures for A58 and provide details on how the measures can be integrated into the project. It also requires usage of climate scenarios developed by the Royal Dutch Meteorological Institute (KNMI), Ministry of Infrastructure and Environment climate guidance, and the flexible adaptation pathways approach. It requires cost-benefit analysis of adaptation measures and analysis of their potential impact on other issues, such as noise and ecological impact. Finally, the RFQ requires that climate resilience of the road and the surrounding area be considered in conjunction with each other.

[59] FHWA, 2017. Transportation Infrastructure Resiliency: A Review of Best Practices in Denmark, the Netherlands, and Norway. https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/gbp_june_2017/index.cfm

Resources for Incorporating Results into Engineering Design

Green Infrastructure Techniques for Coastal Highway Resilience, FHWA, 2016. This FHWA project seeks to improve the resilience of coastal roads, bridges, and highways through implementation of green infrastructure, ecosystem-based approaches.

Transportation Engineering Approaches to Climate Resiliency (TEACR) Study, FHWA, 2017 (expected). This report provides lessons learned for a range of engineering disciplines when considering climate change and extreme weather events in engineering and also discusses analytical processes for addressing climate change and extreme weather events in project level assessments. This work was based on multiple engineering-informed adaptation studies that sought to address climate change concerns, including nine that were conducted as part of this project with a range of State partners.

Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience (Hydraulic Engineering Circular No. 17, 2nd Edition), FHWA, 2016. This document presents detailed technical guidance and methods for assessing the vulnerability of riverine transportation infrastructure to extreme flood events.

Highways in the Coastal Environment: Assessing Extreme Events (Hydraulic Engineering Circular No. 25–Volume 2), FHWA, 2014. This manual provides technical guidance and methods for quantifying the exposure of transportation facilities to sea level rise, storm surge, and wave action.

Tech Brief: Climate Change Adaptation for Pavements, FHWA, 2015. This Tech Brief provides and overview of climate change and pavement-specific impacts, and then addresses specific pavement adaptation strategies that can be implemented now and in the future.

Resilient and Sustainable Transport–Dutch Style: An interim report on bilateral cooperation between FHWA and Rijkwaterstaat, FHWA, 2017. This interim report summarizes information and perspectives gained to date from collaboratively testing U.S. and Dutch climate resilience tools on highway projects in both countries.

Transportation Infrastructure Resiliency: A Review of Practices in Denmark, the Netherlands, and Norway, FHWA, 2017. This report summarizes the information gleaned through an FHWA Global Benchmarking Study on climate resilience practices used by transportation agencies in each of the three countries. It includes international practices on integrating climate projections into highway planning and design procedures, managing uncertainty, and emergency management.

INCORPORATING RESULTS INTO TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS, MAINTENANCE, AND EMERGENCY MANAGEMENT

Transportation systems management and operations (TSMO) includes programs and activities that are focused on improving the efficient use of existing infrastructure, such as traffic management, traffic incident management, traveler information services, and road weather management. Maintenance functions, such as pavement management, vegetation management, and bridge inspection, are designed to preserve and extend the use of transportation infrastructure.

Transportation operations and maintenance functions play vital roles in increasing the transportation system's resilience to climate change and extreme weather events. To increase their resilience to unanticipated shocks to the system, agencies can incorporate climate change considerations into how they plan and execute their TSMO, maintenance, and emergency management programs.

Agencies can use the results of a vulnerability assessment to augment operations and maintenance programs to increase resilience to climate change and extreme weather. To do so, agencies must first understand which TSMO and maintenance decisions are climate sensitive, and then determine how the impacts of climate change will affect those decisions. Decisions are climate-sensitive if their continued effectiveness could be compromised by projected changes in climatic conditions.

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. Consider how existing TSMO, maintenance programs, and emergency response capabilities should evolve to meet the new and emerging requirements of a changing climate.

TSMO and maintenance areas where the impacts of climate change could be considered include:

- **Planning for workforce needs.** Workforce planning includes determining the number of staff required, their locations, and the abilities necessary to monitor, control, report, and maintain the roadway system. An increase in the frequency of extreme weather 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 require additional or unique staff expertise to monitor and respond to new types of climate events.
- **Budgeting for TSMO,** maintenance, and emergency management. Extreme events and long-term changes in climate can affect resource requirements, such as funding needed for annual pavement maintenance costs or for snow removal. The future climate may require different resource allocations and budget planning formulas than today's climate. Agencies should use a strategic approach to allocate investments between improving operations on the average day and improving operations during extreme weather events.
- **Increasing regular maintenance activities.** Cleaning debris out of culverts and storm drains, especially before forecasted extreme weather events, can allow more water to flow when increased precipitation or flooding occur.
- **Adding capacity for smaller infrastructure inspections.** Employing contractors, adding staff, and training existing bridge inspectors can bolster the number of agency practitioners available to cover regular and emergency inspections of smaller assets, such as culverts.
- **Planning for new capital improvements and annual maintenance investments.** Capital improvements should be designed to withstand the climate changes anticipated over their useful life.
- **Assessing future technology and system requirements.** Agencies may require different types of monitoring equipment in order to respond to changing climate conditions. Mobile equipment can improve the speed and accuracy of data collection during inspections. Climate change could also affect where agencies choose to site new equipment and communications systems.
- **Determining future maintenance needs and methods.** Maintenance needs, including those related to pavement rehabilitation, bridge maintenance, construction and maintenance work timelines and timeframes, and vegetation control, may be affected by climate change. Climate stressors can lead to increased asset deterioration, requiring more frequent inspections. However, inspections are 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.
- **Maintaining mobility and safety.** Changes in the frequency of short-term weather events or the types of events that cause traffic disruptions may require changes in operating procedures, resource levels to prepare for and respond to disruptions, and designated evacuation routes.

Examples: Incorporating Results into TSMO, Maintenance, and Emergency Management

- State and local member organizations in New York, New Jersey, and Connecticut rely on the regional coordinating body, Transportation Operations Coordinating Committee (TRANSCOM), 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.
- The Norwegian government uses a suite of interactive tools, many on mobile platforms, to inform the traveling public of weather hazards and road conditions. These tools integrate data such as avalanche forecasts, road closures, and reports from the public. Weather station data, stream gauge data, and road condition information can be accessed from a single location. The application, called xgeo, uses common maps and includes separate access protocols for the public and government employees. Real-time reports from the public can help officials react to road closure events and set up detours.

Resources for Incorporating Results into TSMO, Maintenance, and Emergency Management

Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance: A Primer, FHWA, 2015. This guide provides information and resources to help transportation management, operations, and maintenance staff understand the risks that climate change poses and 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.

International Practices on Climate Adaptation in Transportation, FHWA, 2015. This report examines how transportation agencies in Australia, Canada, Denmark, Korea, New Zealand, the Netherlands, Norway, and the United Kingdom are addressing issues related to adapting highway infrastructure to the impacts of climate change. The report highlights the state of the practice on the following: adaptation frameworks/strategies; climate change risk assessments; selecting adaptation measures and strategies; long-range planning and land use; changes in design standards; maintenance and operations; asset management; and research.

Culvert Management Case Studies: Vermont, Oregon, Ohio, and Los Angeles County, FHWA, 2014. These case studies describe how transportation agencies are increasing resilience of their culvert systems to hydraulic control structure failures through the development of effective culvert management systems and policies.

INCORPORATING RESULTS INTO ASSET MANAGEMENT

Asset management is a process used for managing transportation infrastructure with the objective of improved decisionmaking. Asset management considers the entire life cycle of an asset and aids in determining which programs and projects to invest in to achieve the best long-term benefit. The ultimate goal of transportation asset management is to simultaneously minimize long-term costs while maximizing performance, including asset and system resilience to extreme weather events and climate change. A risk-based asset management system can help agencies anticipate and effectively respond to extreme weather events and climate threats.

MAP-21 required State DOTs to develop risk-based Transportation Asset Management Plans (TAMPs). TAMPs help agencies answer five core questions:

1. What is the current status of our assets?
2. What is the required condition and performance of those assets?
3. Are there critical risks that must be managed?
4. What are the best investment options available for managing the assets?
5. What is the best long-term funding strategy?

To conserve Federal resources and protect public safety, MAP–21 also mandated periodic evaluations to determine if reasonable alternatives exist to roads, highways, or bridges that repeatedly require repair and reconstruction activities.

In 2016, FHWA issued a rule that establishes requirements for State DOTs to perform statewide evaluations to determine if there are reasonable alternatives to roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events (23 CFR 667). The rule also establishes a process for developing State TAMPs. The rule requires each State DOT to establish (1) a process for conducting life-cycle planning (a process to estimate the cost of managing an asset class or sub-group over its whole life with the goal of minimizing costs while preserving or improving the condition), and (2) a process for identifying, evaluating, mitigating, and monitoring risks that can affect conditions of the National Highway System (NHS) (Section 515.7). Relevant risks encompass current and future environmental conditions, including extreme weather and climate change.

Example targets might include a decrease in the percentage of pavement susceptible to melting in extreme heat, or a decrease in the number of bridges susceptible to washout during flooding events.

As part of the rule, States are required to establish performance targets for pavements and bridges. States could set targets for asset resilience to climate change and extreme weather. Example targets might include a decrease in the percentage of pavement susceptible to melting in extreme heat, or a decrease in the number of bridges susceptible to washout during flooding events.

Vulnerability assessments provide useful information for asset management, including data and analysis to: identify critical risks, inform investment decisions, estimate necessary resources for funding elements of the TAMPs, and prioritize

Definitions

Transportation Asset Management

"…Strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost."

MAP-21

Transportation Asset Management Plan Rulemaking

"The development and implementation of an asset management plan…is an important part of the overall MAP-21 framework for enhancing the management and performance of transportation highway infrastructure funded through the Federal-aid highway program. The asset management plan required by section 1106 of MAP-21 will provide States with critical data and identify investment and management strategies to improve or preserve the condition of the assets and the performance of the NHS."

DOT FHWA 23 CFR 515

projects (see Table 3). The relevant exposure, sensitivity, and adaptive capacity indicators developed through a vulnerability assessment can serve as a good model for considering asset risks when developing a TAMP. In addition, results of a vulnerability assessment can be used to evaluate and select appropriate adaptive strategies, such as retrofitting and rebuilding, and improve documentation of the selected strategy.

Similarly, the information collected and stored within a transportation asset management system is useful for conducting future climate change and extreme weather vulnerability assessments. A transportation asset management system with a rich amount of data is particularly advantageous as the availability of data drives the scale and costs of vulnerability assessments. For example, inventories that collect information on asset condition, elevation, and remaining design life can be stored in asset management systems and be used in a vulnerability assessment to help identify which assets are at risk to weather and climate. State DOTs that develop unit-cost data have a means to then estimate recovery costs after an event. Information on post-disaster repairs collected to satisfy the statewide evaluation requirements under 23 CFR 667 can be used as data inputs into vulnerability assessments as well.

Table 3: Mapping of Climate Change/Extreme Weather Factors and a TAMP

TAMP Section	Climate Related Information to Consider
Asset inventory and conditions	Summarize the climate- and weather-related conditions that have affected the system historically. Identify changing climatic conditions that are likely to occur in the future.
Asset management objectives and measures	Define the objectives of the asset management program that relate to system resiliency, redundancy, evacuation, and recovery. Identify the types of assets or network segments that will receive attention with respect to climate- and weather-related disruptions. Define levels of service and measures for climate- and weather-related system operations and conditions. Define short-term and long-term condition targets for resiliency, redundancy, evacuation, and recovery.
Performance gap assessment	Define short-term and long-term asset management planning horizons as they relate to climate/extreme weather factors. Illustrate the performance gap between existing performance levels and future performance levels with respect to system disruption.
Life-cycle cost considerations	In the context of life-cycle costs, discuss the tradeoffs associated with minimizing asset vulnerabilities as part of the normal capital program, versus waiting until an extreme weather event occurs.
Risk management analysis	Within the context for risk management, identify climate/extreme weather event risks to the system. Identify assets that are at most risk. Include a risk register that provides the following for each programmatic risk: likelihood of occurrence, consequences of occurrence, and mitigation activities.
Financial plan	Incorporate into the TAMP financial plan a strategy for funding needed improvements to reduce system risks, whether as part of normal capital investment or as a stand-alone funding initiative.
Investment strategies	Describe typical approaches to minimizing climate- and weather-related risks
Investment asset management process enhancements	Identify priorities for asset management improvement as it relates to climate- and weather-related considerations. Incorporate lessons learned from system disruptions that occur over time.

Source: NCHRP 25-25, Task 94. Integrating Extreme Weather and Adaptation into Transportation Asset Management Plans, 2015.

Examples: Incorporating Results into Asset Management

- The **Los Angeles County Metropolitan Transportation Authority** (Metro) integrated climate risk into its existing asset management system. Metro expanded the system to include new data fields and provided guidelines for assessing climate risk including the identification of assets, screening of assets for criticality, screening assets for vulnerability to changes in climate, screening for indicators of projected rate of change in extreme weather, and assessing the overall risk of the asset.
- The **Metropolitan Atlanta Regional Transit Authority** (MARTA) used the FTA's "Asset Management Guide" to consider ways to adapt to extreme weather events and change in climate. Through this effort, MARTA conducted a vulnerability assessment of its assets and identified associated risks. MARTA then identified entry points in its transit asset management system for climate adaptation strategies and linked this to business units when considering the life cycle management of the assets, balancing resilience efforts with other system performance objectives.
- The **Pennsylvania Department of Transportation** (PennDOT) has characterized climate change as a medium risk to the transportation system and the implementation of the TAMP. The TAMP mentions two specific concerns: (1) an increase in the number and severity of major storms may divert available funds from supporting transportation initiatives to responding to storm events, and (2) climate change may affect asset performance and lead to asset deterioration.
- **Michigan DOT** (MDOT) used its scour critical bridge inventory and analysis framework to determine which assets in the vulnerability assessment were critical. Doing so, in turn, informed the overall risk score. Using existing practices to evaluate asset criticality will allow MDOT to more readily integrate findings into other planning and investment analysis efforts.

Resources for Incorporating Results into Asset Management

Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events (23 CFR Parts 515 and 667), FHWA 2016. This rulemaking details the necessary steps and provides guidance for developing a TAMP as required by section 1106 of MAP-21.

Integrating Extreme Weather into Transportation Asset Management Plans, NHCRP, 2015. This document presents a template and process for State agencies to draw from when integrating extreme weather events and climate change into a TAMP.

Asset Management, Report 5: Building Resilience into Transportation Assets, FHWA, 2013. This report considers ways in which threats including climate change and extreme weather may be addressed in risk-based asset management programs. Management of risks are considered through metrics of redundancy, robustness, and resiliency.

Asset Management, Extreme Weather and Proxy Indicators Pilot projects, FHWA, expected 2018.

Integrating Extreme Weather Risk into Transportation Asset Management, AASHTO, 2012. This white paper details how extreme weather varies from other types of risks and considers extreme weather and climate change entry points in the Transportation Asset Management framework for risk assessment.

Incorporating Risk Management into Transportation Asset Management Plans, FHWA, 2017. This document provides guidance on the risk element of the Transportation Asset Management Plan, defines risk, and provides guidance on how risk can be applied to meet the requirements of a risk-based TAMP.

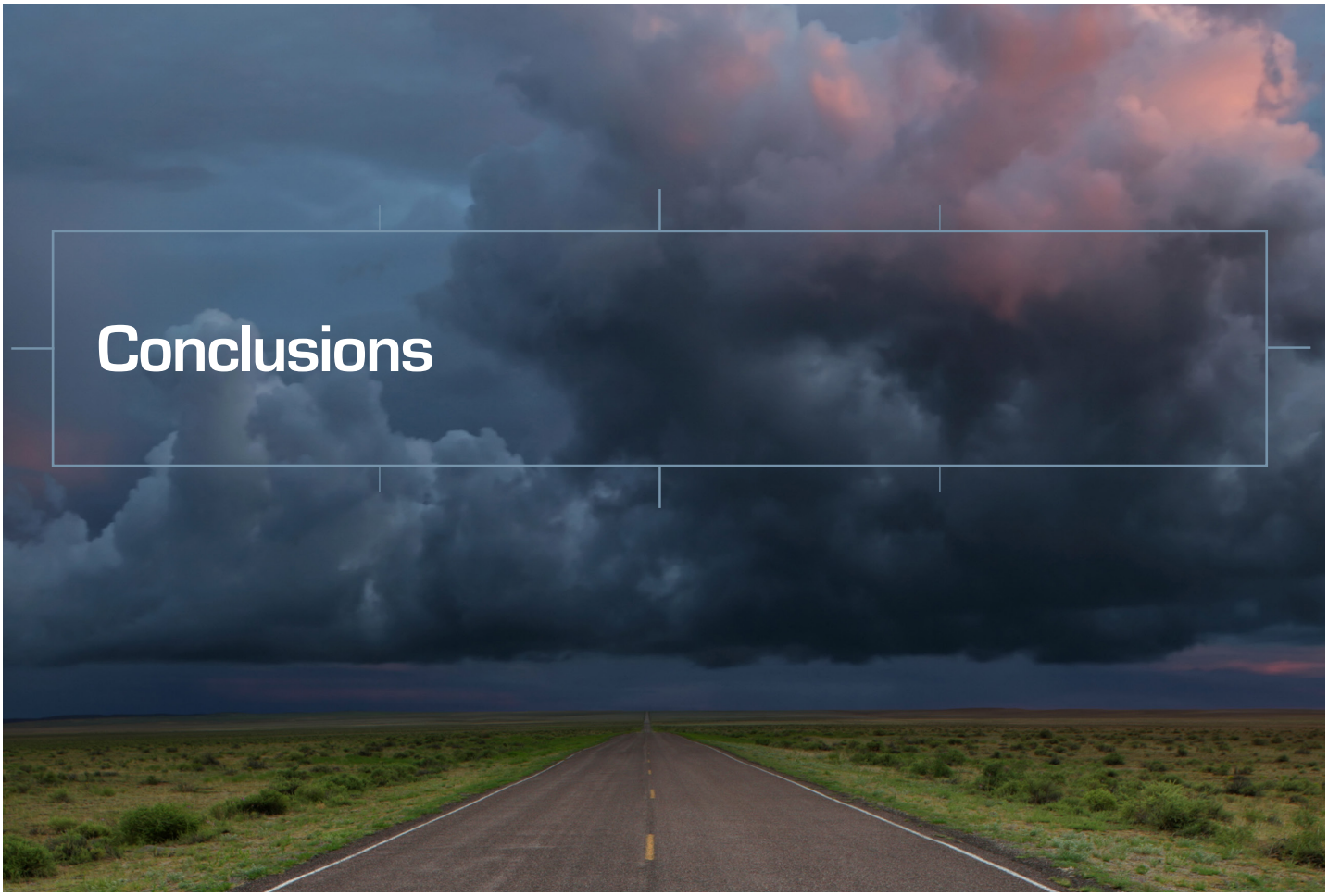
Using a Life Cycle Planning Process to Support Asset Management, FHWA, 2017. This document defines and discusses work to conduct life cycle planning activities as part of Transportation Asset Management. Life cycle planning is a structured sequence of actions to achieve and sustain a desired state of good repair over the life cycle of collections of assets at a minimum practical cost.

MONITOR AND REVISIT

Adapting to climate change is an iterative process that requires monitoring and evaluation to keep adaptation efforts on track with the evolving understanding of climate risks. Agencies should establish monitoring and evaluation processes to assess the success of adaptation strategies and other initiatives that were established based on the assessment findings. As new climate science and data becomes available, agencies may need to reassess their vulnerabilities. The monitoring and evaluation process may identify the need to revisit the assumptions, underlying data, or approaches used in the original vulnerability assessment. The results can also be used to periodically revisit and refine adaptation strategies and processes as needed to ensure continued resilience of transportation infrastructure to climate change.

Key steps in the monitoring and evaluation process include:

- **Establish a monitoring and evaluation plan.** An effective monitoring and evaluation plan will determine the extent to which adaptation strategies and other initiatives based on the vulnerability assessment's findings are meeting their objectives. The plan should include evaluation questions, measurable objectives, and clear indicators or metrics.
- **Engage stakeholders.** Transportation agencies, transportation systems, and individual transportation assets involve many stakeholders. Engaging these stakeholders in the monitoring and evaluation process can create buy-in, build credibility, and increase the likelihood that monitoring and evaluation efforts will be supported. Ideally, agencies will engage stakeholders at the beginning of a vulnerability assessment or subsequent adaptation program, keep them informed and involved, and include them in the monitoring and evaluation process.
- **Monitor and collect data on relevant indicators.** Monitoring entails the systematic collection of information. It should be a periodically recurring task that begins in the planning stage of the project. Monitoring allows results, processes, and experiences to be documented and used as a basis to steer decisionmaking and future planning. Monitoring also allows an agency to check progress against plans. The data acquired through monitoring are used for evaluation.
- **Evaluate the project and its outcomes.** Evaluation can occur as an ongoing part of an adaptation project and/or once the project is completed. Data collected from monitoring will help inform ongoing decisions and suggest improvements for future efforts.
- **Revisit.** The monitoring and evaluation process may identify the need to revisit the assumptions, underlying data, or approaches used in the original vulnerability assessment. Information gleaned from monitoring and evaluation can more generally be used to inform project and program planning, improve processes, share lessons learned, and continue to engage stakeholders.



Conclusions

As climate change and extreme weather continue to present significant and growing risks to the nation's vital transportation infrastructure, it is imperative that transportation agencies understand and continue to address these impacts. Conducting a climate change vulnerability assessment will inform agencies about the threats to their assets and provide vital information to effectively address those vulnerabilities. As highlighted throughout the Framework, there are many opportunities within the transportation decisionmaking process to improve the resilience of transportation infrastructure to climate change. An agency can use the results of a vulnerability assessment to develop adaptation strategies that will address the vulnerabilities can also incorporate results into transportation planning and project prioritization, environmental review, project design, operations and maintenance, and asset management.

While the Framework provides an overview of each of the steps in conducting a vulnerability assessment, transportation agencies that are beginning to conduct an assessment of their own may wish to dig deeper. The resources mentioned throughout the Framework and summarized in Appendix A provide more detailed information that agencies can refer to as they develop the scope of their assessment, collect data, assess vulnerabilities, and integrate results into the decisionmaking process. In addition, agencies may learn from the experiences of their peers, including State DOTs and MPOs that participated in FHWA's climate resilience pilot program. A summary of the various FHWA climate resilience pilots are included in Appendix C.

Moving forward, FHWA will build off of the information in this Framework and continue to work with its partners to provide transportation agencies with resources to assess vulnerabilities and build their resilience to climate change and extreme weather.

Appendix A: Summary of Resources

Appendix A provides a summary of the resources included in each section of the Framework.

GENERAL RESOURCES

FHWA Climate Change Resilience Pilots

https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/index.cfm

In two groups of pilot projects, FHWA worked with over twenty State DOTs and MPOs to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency. Each of the individual pilot efforts produced a final report that outlines the project methodology, outcomes, and key findings. The individual reports provide useful information for agencies who are interested in conducting similar efforts. For example:

- The Washington DOT's report from its first pilot outlines the key steps the agency took in its process, which many agencies replicated due to its qualitative and stakeholder driven approach.
- The Iowa DOT's final report provides details on the methodology the agency used to integrate climate projections of rainfall within a river system model to predict river flood response to climate change.
- The Oregon DOT's final report details how the agency identified vulnerable hazard sites and evaluated a range of site-specific adaptation strategies that address landslides, coastal erosion, and storm surge hazards.

2013–2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned, and Recommendations

https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/final_report/index.cfm

This report highlights results and lessons learned from the 19 FHWA climate resilience pilots. The report also identifies needs and recommended next steps from the pilot program.

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

https://www.nap.edu/download/22473

TRB's National Cooperative Highway Research Program (NCHRP) Report 750 provides guidance on adaptation strategies to the likely impacts of climate change through 2050 in the planning, design, construction, operation, and maintenance of infrastructure assets in the United States (and through 2100 for sea level rise).

International Climate Change Adaptation Framework for Road Infrastructure

https://www.piarc.org/en/order-library/23517-en-International%20climate%20change%20adaptation%20framework%20for%20road%20infrastructure.htm

The World Road Association developed this report to help member countries adopt a consistent approach to analyze the effects of climate change on their road networks and thus help them identify, propose and prioritize the most appropriate measures to mitigate risks associated with extreme weather events.

Adaptation Clearinghouse—Transportation Sector Case Studies

http://www.adaptationclearinghouse.org/sectors/transportation/case-studies-b.html

The site, hosted by the Georgetown Climate Center, features hundreds of transportation sector case studies that highlight examples of how adaptation has been incorporated into decisionmaking at all stages of the transportation life cycle: assessing vulnerability, planning, design, and operations and maintenance.

RESOURCES FOR ARTICULATING OBJECTIVES

Video: Articulating the Objectives of a Vulnerability Assessment.

https://www.youtube.com/watch?v=9t4ZBJNk4dk

In this short video, Sandy Salisbury, Roadside and Site Development Manager for WSDOT, describes the importance of setting objectives, the process that WSDOT used to identify the objectives of its vulnerability assessment, and the need to revisit and refine objectives over time.

RESOURCES FOR SELECTING TRANSPORTATION ASSETS

Video: **Selecting Assets to Evaluate in a Vulnerability Assessment,** FHWA, 2015.

https://youtu.be/8BZEWLENtAc

In this short video, Tian Feng, district architect for the San Francisco BART, describes how his agency selected critical assets to evaluate in its vulnerability assessment.

Assessing Criticality in Transportation Adaptation Planning, FHWA, 2014.

https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/criticality_guidance/

This memo discusses approaches for narrowing the universe of transportation assets to focus on in a climate change vulnerability assessment by evaluating their criticality. It discusses common challenges associated with assessing criticality, options for defining criticality and identifying scope, and the process of applying criteria and ranking assets.

RESOURCES FOR SELECTING CLIMATE VARIABLES

Transportation Climate Change Sensitivity Matrix, USDOT, 2015.

https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/modules/sensitivity_matrix.xlsm

The USDOT's Sensitivity Matrix documents the sensitivity of transportation modes and sub-modes (including roads, rail, airports, ports and waterways, and oil and gas pipelines) to 11 climate impacts: storm surge, wind, sea level rise/extreme high tides/coastal flooding, inland flooding, drought, increased temperatures and extreme heat, wildfires, dust storms, permafrost thaw, changes in freeze/thaw, and winter storms. Users may select a specific transportation mode and explore its sensitivity to a range of impacts, or they may select a specific climate impact and explore the sensitivity of different modes to that impact.

The Use of Climate Information in Vulnerability Assessments, FHWA, 2011.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/vulnerability_assessments/index.cfm

This memorandum focuses on the use of climate information when performing a vulnerability assessment. The memorandum describes several sources of precipitation and temperature information, and provides some recommendations on how this information can be used by transportation planners as they consider their climate-related vulnerabilities.

Synthesis of Approaches for Addressing Resilience in Project Development, FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm

This report synthesizes lessons learned and innovations from a variety of recent FHWA studies and pilots to help transportation agencies address resilience concerns at the asset level in engineering-informed adaptation studies. Appendix B provides a summary of the derived climate change variables used in the various FHWA case studies.

RESOURCES FOR OBTAINING AND USING TEMPERATURE AND PRECIPITATION PROJECTIONS

Reports

Climate Change Impacts in the United States. U.S. National Climate Assessment, U.S. Global Change Research Program, 2014.

http://s3.amazonaws.com/nca2014/high/NCA3_Climate_Change_Impacts_in_the_United%20States_HighRes.pdf

This report assesses the science of climate change and its related impacts and responses by region and for various sectors, including transportation.

The Gulf Coast Study, Phase 2. Temperature and Precipitation Projections for the Mobile Bay Region, FHWA, 2012.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task2/mobile_infrastructure/mobile_climate_report.pdf

This report describes a general approach for developing the projections needed to quantify future changes in temperature and precipitation exposure for any regional or sectoral analysis. It also describes the specific datasets and methods selected for and used in the analysis for the greater Mobile Bay region, including a description of the observational data, global climate models, future scenarios, and downscaling methods.

The Use of Climate Information in Vulnerability Assessments, FHWA 2011.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/vulnerability_assessments/index.cfm

This memorandum focuses on the use of climate information when performing a vulnerability assessment. The memorandum includes discussion of using historical climate information and includes information on potential data sources.

Regional Climate Processes and Projections for North America: CMIP3/CMIP5 Differences, Attribution and Outstanding Issues, NOAA, 2014.

http://docs.lib.noaa.gov/noaa_documents/OAR/CPO/TR_OAR_CPO/CPO-2.pdf

This report summarizes the key differences and changes from CMIP3 to CMIP5.

Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience (Hydraulic Engineering Circular No. 17, 2nd Edition). FHWA, 2016.

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf

This document presents detailed technical guidance and methods for assessing the vulnerability of transportation infrastructure to extreme flood events in riverine environments. It includes information about downscaling climate data for use in hydraulic engineering.

Climate Model Comparison Tool, The Infrastructure and Climate Network (ICNet).

http://theicnet.org/?page_id=50

This webpage provides detailed information on selecting the appropriate global climate model or collection of models for analysis.

Video – **Downscaling global climate models.**

http://nowuseeit.state.tn.us/Mediasite/Play/a787af53520f49c1b-76fad04a77c88e01d

In this 47-minute video from FHWA's 2012 National Hydraulic Engineering Conference in Nashville, Tennessee, Dr. Katharine Hayhoe, Director of the Climate Science Center at Texas Tech University, describes the process of downscaling global climate models to regional scales.

Online Databases and Tools

Data sources that have projections of future climate change from many different models for various emissions scenarios include:

U.S. DOT's CMIP Climate Data Processing Tool

https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/

This tool processes statistically downscaled climate model data from the World Climate Research Programme's CMIP3 and CMIP5 into relevant temperature and precipitation statistics for transportation planners. These statistics include changes in the frequency of very hot days and extreme precipitation events and other climate variables that may affect transportation infrastructure and services in the near-term, mid-term, and end-of-century.

The U.S. Geological Survey's National Climate Change Viewer.

https://www2.usgs.gov/climate_landuse/clu_rd/nccv.asp

The web viewer shows climate projections at the county and State level, based on statistically downscaled CMIP5 data for moderate and high emissions scenarios. This resource includes projections of climate variables based on daily high temperatures, low temperatures, and precipitation for near-term, mid-term, and end-of-century. In addition, these statistically downscaled projections were used to drive a simple water balance model to estimate runoff, snow, soil water storage, and evaporative deficit.

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections.

https://www.fhwa.dot.gov/exit.cfm?link=https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

This archive provides downloadable climate and hydrological simulations at fine spatial resolution from 1950 to 2099 (as well as climate and hydrological gridded observation data). It contains climate projections for the contiguous U.S., CMIP3 hydrologic projections over the western U.S., and CMIP5 hydrology projections over the contiguous U.S. This resource provides: statistically downscaled climate model data of high temperatures, low temperatures, and precipitation that is used by the USDOT CMIP Climate Data Processing Tool; soil moisture content, snow water equivalent, total runoff, and actual and potential evapotranspiration.

The U.S. Geological Survey's USGS Geo Data Portal.

https://cida.usgs.gov/gdp/

The data portal provides access to numerous climate datasets for particular areas of interest. Through the portal, users can create tailored projections for impact analysis by identifying the regional area and projection datasets of interest, along with a choice of treatment for averaging across model grid c ells within the regional area.

North American Regional Climate Change Assessment Program (NARCCAP).

https://www.fhwa.dot.gov/exit.cfm?link=http://www.narccap.ucar.edu/about/index.html

The website provides access to a set of regional climate models (RCMs) driven by a set of atmosphere-ocean general circulation models (AOGCMs) over a domain covering the contiguous U.S. and most of Canada.

U.S. Geological Survey's StreamStats.

https://water.usgs.gov/osw/streamstats/

This Web application incorporates GIS to provide users with access to an assortment of analytical tools that are useful for a variety of water-resources planning and management purposes, and for engineering and design purposes.

Websites that have historical weather and climate data available include:

- NOAA's **Climate.gov.** A source of timely and authoritative scientific data and information about climate.
- NOAA's National Center for Environmental Information, formerly the National Climatic Data Center. Provides access to an array of climate datasets at **www.ncdc.noaa.gov** and **www.ncdc.noaa.gov/climate-monitoring.**
- **NOAA's Precipitation Frequency Data Server (Atlas 14).** A point-and-click interface developed to deliver NOAA Atlas 14 precipitation frequency estimates and associated information. Available at *https://hdsc.nws.noaa.gov/hdsc/pfds/.*
- **U.S. Historical Climatology Network data.** A data set of daily and monthly meteorological variables from observing stations around the contiguous U.S. U.S. Available at *http://cdiac.ess-dive.lbl.gov/epubs/ndp/ushcn/ushcn.html*

RESOURCES FOR RIVERINE HYDROLOGY ANALYSIS

Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience (Hydraulic Engineering Circular No. 17, 2nd Edition). FHWA, 2016.

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf

This document presents detailed technical guidance and methods for assessing the vulnerability of transportation infrastructure to extreme flood events in riverine environments.

RESOURCES FOR OBTAINING AND USING SEA LEVEL RISE PROJECTIONS

Reports

Global and Regional Sea Level Rise Scenarios for the United States, NOAA, 2017.

https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

The report presents a range of global mean sea level rise scenarios, and discusses projected relative sea level rise for different regions of the U.S.

North Atlantic Coast Comprehensive Study: Resilience Adaptation to Increasing Risk, USACE, 2015.

http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NACCS_main_report.pdf

This comprehensive study was conducted to address the flood risks of vulnerable coastal populations in areas that were affected by Hurricane Sandy (from New Hampshire to Virginia). The study includes an analysis of sea level and climate scenarios, and a discussion of how those scenarios might affect coastal populations, infrastructure, ecosystems, and implementation of risk management strategies within the study area. The report includes a nine-step Coastal Storm Risk Management Framework that was developed to help all stakeholders identify the risk of coastal flooding and evaluate the full range of strategies available to reduce those risks.

Sea level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future, National Research Council, 2012.

www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington

This report examines all aspects of relative sea level rise on the West Coast (including land mass movements). The study includes projections of sea level rise along the coast for the years 2030, 2050, and 2100, taking into account regional factors that affect sea level.

Technical Guidance

Highways in the Coastal Environment: Assessing Extreme Events (Hydraulic Engineering Circular No. 25 – Volume 2), FHWA, 2014.

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf

This manual provides technical guidance and methods for quantifying the exposure of transportation facilities to sea level rise, storm surge, and wave action.

Procedures to Evaluate Sea Level Change: Impacts, Responses and Adaptation, USACE, 2014.

http://www.publications.usace.army.mil/Portals/76/Publications/EngineerTechnicalLetters/ETL_1100-2-1.pdf

This technical letter provides guidance for understanding the direct and indirect physical and ecological effects of projected future sea level change on USACE projects and systems of projects, and considerations for adapting to those effects.

Incorporating Sea Level Change in Civil Works Programs, USACE, 2013.

http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1100-2-8162.pdf

This regulation provides USACE guidance for incorporating the direct and indirect physical effects of projected future sea level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects.

Guidance on Incorporating Sea Level Rise, Caltrans, 2011.

https://www.fhwa.dot.gov/exit.cfm?link=http://www.dot.ca.gov/ser/downloads/sealevel/guide_incorp_slr.pdf

Provides guidance to Caltrans staff on how to assess the vulnerability of transportation projects to sea level rise impacts and incorporate adaptation into the programming and design of vulnerable projects.

Online Databases and Tools

Sea level Change Curve Calculator, USACE.

http://www.corpsclimate.us/ccaceslcurves.cfm

A tool that quickly estimates the relative sea level rise at a given location for each year until 2100, assuming certain rates of sea level rise and local land subsidence/uplift.

Digital Coast, NOAA.

https://coast.noaa.gov/digitalcoast/

This NOAA-sponsored website provides coastal data and tools, including the **Sea Level Rise Viewer** *(https://coast.noaa.gov/digitalcoast/tools/slr.html)* a web mapping tool to visualize community-level impacts from coastal flooding or sea level rise. The viewer shows depth and extent of inundation for the entire U.S. coastline for six sea level rise scenarios, ranging from current (0 foot) to 6 feet (in 1-foot increments).

Video: **Forecasting Sea Level Rise for Maryland,** MD Sea-Grant, 2013.

https://www.youtube.com/watch?v=RCc3C89qxOM

In this short video, scientists describe how subsidence in the Chesapeake Bay is impacting overall sea level rise in the area.

RESOURCES FOR STORM SURGE PREDICTIONS

Highways in the Coastal Environment: Assessing Extreme Events (Hydraulic Engineering Circular No. 25 – Volume 2), FHWA, 2014.

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf

This manual provides technical guidance and methods for quantifying the exposure of transportation facilities to sea level rise, storm surge, and wave action.

FEMA Flood Map Service Center, FEMA.

https://msc.fema.gov/portal

The official public source for flood hazard information produced in support of the National Flood Insurance Program.

North Atlantic Coast Comprehensive Study Report, USACE, 2015.

http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NACCS_main_report.pdf

USACE developed this report to help local communities better understand changing flood risks associated with climate change and to provide tools to help those communities better prepare for future flood risks. The report builds on lessons learned from Hurricane Sandy.

RESOURCES FOR ASSESSING VULNERABILITY

Video: **Identifying and Rating Vulnerabilities.**

https://www.youtube.com/watch?v=QvedJ2k7ils

In this short video, Sandy Salisbury, roadside and site development manager for WSDOT, describes how WSDOT conducted its vulnerability assessment through regional workshops.

2013–2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned, and Recommendations. FHWA, 2016.

https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/final_report/index.cfm

Over the course of two years, FHWA worked with State DOTs and MPOs to undertake 19 assessments of climate change and extreme weather vulnerability and adaptation options on their transportation systems. The pilots used and built on FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework. This report highlights results and lessons learned from those efforts.

Vulnerability Assessment Scoring Tool (VAST). USDOT, 2015.

User guide: *https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/scoring_tools_guide/*

Tool: *https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/scoring_tools_guide/vast.xlsm*

This **Excel spreadsheet** tool provides step-by-step guidance through the process of conducting a quantitative, indicator-based vulnerability screen. Users enter information on their assets, select the parameters for the analysis, and select indicators to evaluate exposure, sensitivity, and adaptive capacity. The tool then calculates vulnerability scores for each asset on a scale of 1 to 4. The VAST tool was developed to facilitate screening or scoring of a large number of assets; the user can then decide whether a more in-depth analysis is needed on specific vulnerable assets identified through VAST.

The Gulf Cost Study: Screening for Vulnerability, FHWA, 2014.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.1/index.cfm

This report describes the methodology and findings of a high-level vulnerability assessment of the transport system in Mobile, Alabama. This analysis used an indicators approach that scored assets and climate stressors against exposure, sensitivity, and adaptive capacity indicators. Then, an overall vulnerability score for the asset to the climate stressor was developed by weighting and combining the exposure, sensitivity, and adaptive capacity scores. Stakeholders also vetted preliminary results to ensure key assets that did not score as high were included. Detailed information on the scoring and weighting systems used for each indicator is included in the Appendices.

ROADAPT, Guideline B: Performing a Quick scan on risk due to climate change, Conference of European Directors of Roads (CEDR), 2015.

http://www.cedr.eu/download/other_public_files/research_programme/call_2012/climate_change/roadapt/ROADAPT_Part_B_-_quickscan_guidelines.pdf

The Quickscan approach is a method for performing a preliminary climate change risk assessment that uses three desktop planning efforts and three workshops to identify consequences, probabilities, risk, location, and an action plan for roadways. The process results in a short list of locations that will receive action plans, which can include new actions or existing activities that take place in operations and maintenance activities. Suggested stakeholders to involve in the Quickscan approach include transportation experts, economists, road engineers, communications experts, climate specialists, and asset operators.

ROADAPT, Guideline C: GIS-aided vulnerability assessment for roads, CEDR, 2015.

http://www.cedr.eu/download/other_public_files/research_programme/call_2012/climate_change/roadapt/ROADAPT_Part_C_-_guidelines_on_vulnerability_assessment_method.pdf

The ROADAPT Vulnerability Assessment (VA) combines multiple indicators of climate change vulnerability in a GIS-based format to evaluate the vulnerability of road segments or assets relative to one another.

RESOURCES FOR CONDUCTING ENGINEERING INFORMED ASSESSMENTS

Synthesis of Approaches for Addressing Resilience in Project Development, FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm

This report provides lessons learned for a range of engineering disciplines when considering climate change and extreme weather events in engineering and also discusses analytical processes for addressing climate change and extreme weather events in project level assessments. This work was based on multiple engineering-informed adaptation studies that sought to address climate change concerns, including nine that were conducted as part of this project with a range of State partners.

Post Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/hurricane_sandy/index.cfm

This final report from the study includes information on damage and disruption from Hurricane Sandy on the region's transportation systems, along with that of Hurricane Irene, Tropical Storm Lee, and Halloween Nor'easter Alfred. The report also includes engineering-informed assessments of climate vulnerabilities and risks and evaluation of potential adaptation strategies for a selection of transportation facilities–roads, bridges, tunnels, rail, and ports–that can be considered for these and similar facilities.

The Adaptation Decision-Making Assessment Process (ADAP), FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

ADAP is an 11-Step process that was developed to structure the asset level analyses conducted as part of the TEACR project. Its steps fit well with the elements listed in section 5.4.

Engineering Assessments of Climate Change Impacts and Adaptation Measures, FHWA, 2014.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.2/index.cfm

This report discusses a series of engineering assessments on specific transportation facilities in Mobile, AL that evaluated whether those facilities might be vulnerable to projected changes in climate, and what specific adaptation measures could be effective in mitigating those vulnerabilities.

RESOURCES FOR CONSIDERING RISK

Video: Building a Risk Management Response to Climate Change, FHWA, 2015.

https://www.youtube.com/watch?v=4RX0BDdM1h8

In this short video, Klaus Jacob and Cynthia Rosenzweig of the New York City Panel on Climate Change describe New York's risk-based approach to addressing vulnerability, including the use of flexible adaptation pathways and periodic reassessment to realign objectives with new information.

RESOURCES FOR IDENTIFYING, ANALYZING AND PRIORITIZING ADAPTATION OPTIONS

Transportation Engineering Approaches to Climate Resiliency (TEACR) Study, FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/

This report provides lessons learned for a range of engineering disciplines when considering climate change and extreme weather events in engineering and also discusses analytical processes for addressing climate change and extreme weather events in project level assessments. This work was based on multiple engineering-informed adaptation studies that sought to address climate change concerns, including nine that were conducted as part of this project with a range of State partners.

Post Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, FHWA, 2017.

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ROADAPT Guideline part E: Selection of adaptation measures. Conference of European Directors of Roads, 2015.

https://climate-adapt.eea.europa.eu/metadata/guidances/roadapt-guidelines-for-adaptation-of-road-infrastructure-to-climate-change

Provides process for selecting adaptation options and matrix of measures by category (hydraulic capacity of culverts, hydraulic capacity of road drainage systems, stability of road embankments after flooding, landslides, tunnel uplift, embankment erosion, heat stress on pavements, spring thaw pavement deterioration, and traffic management in situations with operation restrictions). The Guidelines include a companion **database of adaptation strategies.**

International Climate Change Adaptation Framework for Road Infrastructure. World Road Association, 2015.

https://www.piarc.org/en/order-library/23517-en-International%20climate%20change%20adaptation%20framework%20for%20road%20infrastructure.htm

This framework includes resources and instructions to help transportation and road decisionmakers cope with the negative effects of climate change and manage them systematically and efficiently. This document guides road authorities through the process of increasing the resilience of their networks and assets through four stages. Stage 3, Developing and Selecting Adaptation Responses and Strategies, includes information on how to conduct a multi-criteria analysis.

RESOURCES FOR CONDUCTING AN ECONOMIC ANALYSIS

Synthesis of Approaches for Addressing Resilience in Project Development (Chapter 6), FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm

This report summarizes a range of techniques and lessons learned on conducting economic analysis of adaptation measures based on pilots to help transportation agencies address changing climate conditions and extreme weather events at the asset level.

Comparison of Economic Analysis Methodologies and Assumptions: Dyke Bridge in Machias, Maine, FHWA, 2016.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/dyke_bridge/index.cfm

This is one of nine engineering case studies conducted under the TEACR Project. This case study focused on comparing the approaches and outcomes of two climate change adaptation economic assessments.

Benefit-Cost Analysis Guidance for TIGER Grant Applicants, U.S. DOT.

https://www.transportation.gov/sites/dot.gov/files/docs/TIGER_BCA_Guidance.pdf

This document provides general information and guidance on conducting a BCA. The supplemental **Benefit-Cost Analysis**

(BCA) Resource Guide provides technical information on monetizing benefits and costs, as well as guidance on methodology.

Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses—2016 Revision, U.S. DOT, 2016.

https://www.transportation.gov/sites/dot.gov/files/docs/VSL%20Guidance%202016.pdf

Agency guidance on the value of a statistical life to use when assessing the benefits of preventing fatalities. The guidance also establishes policies for assigning comparable values to prevention of injuries.

Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, U.S. DOT, 2015.

https://www.transportation.gov/sites/dot.gov/files/docs/Revised%20Departmental%20Guidance%20on%20Valuation%20of%20Travel%20Time%20in%20Economic%20Analysis.pdf

Outlines procedures to determine the value of travel time savings to use in agency benefit-cost or cost-effective analysis of regulatory actions or investments.

Guidelines for Preparing Economic Analyses, U.S. Environmental Protection Agency, 2010.

https://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses#download

The guidelines provide a scientific framework and guidance on analyzing the benefits, costs, and economic impacts of regulations and policies, including assessing the distribution of costs and benefits among various segments of the population.

ROADAPT Guideline D: Socio-economic impacts analysis, Conference of European Road Directors, 2015.

http://www.cedr.eu/download/other_public_files/research_programme/call_2012/climate_change/roadapt/ROADAPT_Part_D_guidelines_on_socioeconomic_impactassessment.pdf

This report, part of the overall ROADAPT guidelines, contains details on how to perform a socio-economic impact assessment of the consequences of weather events and the impact of adaptation strategies.

RESOURCES FOR INCORPORATING RESULTS INTO TRANSPORTATION PLANNING

Resilience and Transportation Planning, FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/ratp/index.cfm

This fact sheet outlines updates to the metropolitan and statewide transportation planning regulations to reflect new FAST Act requirements to address resilience and natural disaster risks.

Addressing Climate Change Adaptation in Regional Transportation Plans: A Guide for California MPOs and RTPAs, Caltrans 2013.

http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/FR3_CA_Climate_Change_Adaptation_Guide_2013-02-26_.pdf

This guide is intended to be a resource to support MPOs and RTPAs in incorporating climate change impacts into their decisionmaking and planning processes. The guide provides MPOs and RTPAs with: (1) background on climate adaptation; (2) recommended data and information to assist in incorporating climate considerations into regional planning; and (3) a step-by-step process for integrating climate risks into plans.

RESOURCES FOR INCORPORATING RESULTS INTO ENVIRONMENTAL REVIEW

Climate Change in NEPA Case Studies, FHWA.

https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/index.cfm

This series of case studies explores examples of how different projects have used their NEPA or other environmental reviews to plan for climate change impacts.

Synthesis of Approaches for Addressing Resilience in Project Development (Chapter 6), FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm

This document provides a brief overview of where and how engineering-informed adaptation studies can be incorporated into the transportation project development process, including environmental review.

RESOURCES FOR INCORPORATING RESULTS INTO ENGINEERING

Green Infrastructure Techniques for Coastal Highway Resilience, FHWA, 2016.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/index.cfm

This FHWA project seeks to improve the resilience of coastal roads, bridges, and highways through implementation of green infrastructure, ecosystem-based approaches.

Transportation Engineering Approaches to Climate Resiliency (TEACR) Study, FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/

This report provides lessons learned for a range of engineering disciplines when considering climate change and extreme weather events in engineering and also discusses analytical processes for addressing climate change and extreme weather events in project level assessments. This work was based on multiple engineering-informed adaptation studies that sought to address climate change concerns, including nine that were conducted as part of this project with a range of State partners.

Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience (Hydraulic Engineering Circular No. 17, 2nd Edition). FHWA, 2016.

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf

This document presents detailed technical guidance and methods for assessing the vulnerability of riverine transportation infrastructure to extreme flood events.

Highways in the Coastal Environment: Assessing Extreme Events (Hydraulic Engineering Circular No. 25 – Volume 2), FHWA, 2014.

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf

This manual provides technical guidance and methods for quantifying the exposure of transportation facilities to sea level rise, storm surge, and wave action.

Tech Brief: Climate Change Adaptation for Pavements. FHWA, 2015.

https://www.fhwa.dot.gov/pavement/pub_details.cfm?id=959

This Tech Brief provides and overview of climate change and pavement-specific impacts, and then addresses specific pavement adaptation strategies that can be implemented now and in the future.

Resilient and Sustainable Transport—Dutch Style: An interim report on bilateral cooperation between FHWA and Rijkwaterstaat. FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/dutch_style/index.cfm

This interim report summarizes information and perspectives gained to date from collaboratively testing U.S. and Dutch climate resilience tools on highway projects in both countries.

Transportation Infrastructure Resiliency: A Review of Practices in Denmark, the Netherlands, and Norway. FHWA, 2017.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/gbp_june_2017/index.cfm

This report summarizes the information gleaned through an FHWA Global Benchmarking Study on climate resilience practices used by transportation agencies in each of the three countries. It includes international practices on integrating climate projections into highway planning and design procedures, managing uncertainty, and emergency management.

RESOURCES FOR INCORPORATING RESULTS INTO TSMO, MAINTENANCE, AND EMERGENCY MANAGEMENT

Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance: A Primer, FHWA, 2015.

https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf

This guide provides information and resources to help transportation management, operations, and maintenance staff understand the risks that climate change poses and 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.

International Practices on Climate Adaptation in Transportation, FHWA, 2015.

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/international_practices/

This report examines how transportation agencies in Australia, Canada, Denmark, Korea, New Zealand, the Netherlands, Norway, and the United Kingdom are addressing issues related

to adapting highway infrastructure to the impacts of climate change. The report highlights the state of the practice on the following: adaptation frameworks/strategies; climate change risk assessments; selecting adaptation measures and strategies; long range planning and land use; changes in design standards; maintenance and operations; asset management; and research.

Culvert Management Case Studies: Vermont, Oregon, Ohio, and Los Angeles County. FHWA, 2014.

https://www.fhwa.dot.gov/asset/pubs/hif14008.pdf

These case studies describe how transportation agencies are increasing resilience of their culvert systems to hydraulic control structure failures through the development of effective culvert management systems and policies.

RESOURCES FOR INCORPORATING RESULTS INTO ASSET MANAGEMENT

Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events (23 CFR Parts 515 and 667), FHWA 2016.

https://www.regulations.gov/document?D=FHWA-2013-0052-0064

This rulemaking details the necessary steps and provides guidance for developing a TAMP as required by section 1106 of MAP-21.

Integrating Extreme Weather into Transportation Asset Management Plans, NHCRP, 2015.

https://www.fhwa.dot.gov/exit.cfm?link=http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(94)_FR.pdf

This document presents a template and process for State agencies to draw from when integrating extreme weather events and climate change into a TAMP.

Video: Integrating Climate into Asset Management, FHWA, 2015.

https://www.fhwa.dot.gov/exit.cfm?link=https://www.youtube.com/watch?v=hr2Q4sOsyT4

In this short video, Butch Wlaschin, director of the Federal Highway Administration's Office of Asset Management, Pavements and Construction, describes the benefits of integrating climate change vulnerability information into asset management systems.

Asset Management, Report 5: Building Resilience into Transportation Assets, FHWA, 2013.

https://www.fhwa.dot.gov/asset/pubs/hif13018.pdf

This report considers ways in which threats including climate change and extreme weather may be addressed in risk-based asset management programs. Management of risks are considered through metrics of redundancy, robustness, and resiliency.

Integrating Extreme Weather Risk into Transportation Asset Management, AASHTO, 2012.

http://climatechange.transportation.org/pdf/extrweathertamwhitepaper_final.pdf

This white paper details how extreme weather varies from other types of risks and considers extreme weather and climate change entry points in the Transportation Asset Management framework for risk assessment.

Incorporating Risk Management into Transportation Asset Management Plans, FHWA, 2017.

https://www.fhwa.dot.gov/asset/pubs/incorporating_rm.pdf

This document provides guidance on the risk element of the Transportation Asset Management Plan, defines risk, and provides guidance on how risk can be applied to meet the requirements of a risk-based TAMP.

Using a Life Cycle Planning Process to Support Asset Management, FHWA, 2017.

https://www.fhwa.dot.gov/asset/pubs/life_cycle_planning.pdf

This document defines and discusses work to conduct life cycle planning activities as part of Transportation Asset Management. Life cycle planning is a structured sequence of actions to achieve and sustain a desired state of good repair over the life cycle of collections of assets at a minimum practical cost.

Appendix B: Glossary

100-year storm
Term used to define a rainfall event that statistically has a 1-percent change of occurring in a given year or will happen only once every 100 years. This term is frequently used in the media and by the public but can be misinterpreted.

7-day maximum temperature
The highest temperature recorded during a seven-day period. The most common reference is to the daily maximum temperature or "high."

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.

Adaptive capacity
Refers to the ability of a transportation asset or system to adjust, repair, or flexibly respond to damage caused by climate variability or extreme weather.

Asset
Throughout the Framework, the term asset refers to both physical transportation infrastructure such as roads, rails, and bridges as well as support facilities, vehicles, intelligent transportation systems, and ecosystem-related projects.

Asynchronous Regression Model
A statistical process for estimating the linear relationship between observation and present simulation that is determined after sorting them in ascending order.

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.

Climate projection
A projection of the response of the climate system to emissions scenarios of GHGs often based upon simulations by climate models. Climate projections depend upon the emission/concentration/radiative-forcing scenario used, which are based on assumptions concerning, e.g., future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Climate stressor, hazard, or threat
The magnitude of the climate variable that may harm the transportation system or asset.

Climate variable
A characteristic of the climate that affects the transportation system. The climate variables most often analyzed in a transportation vulnerability assessment are temperature, precipitation, sea level, and river discharge.

Downscaling
A method that derives local- to regional-scale information from larger-scale models or data analyses.

Emissions scenario
A plausible representation of the future development of emissions of GHGs based on a coherent and internally consistent set of assumptions about driving forces (such as technological change, demographic and socioeconomic development) and their key relationships. Concentration scenarios, derived from emissions scenarios, are used as input to a climate model to compute climate projections.

Exceedance Precipitation Event
The exceedance precipitation event describes the statistical chance of an event occurring in any given year. For example, a 0.2% exceedance precipitation event means that a precipitation event of that magnitude has a .2 percent change of happening in any given year.

Exposure
Refers to whether an asset or system is located in an area experiencing direct effects of climate variability and extreme weather events. Exposure is a prerequisite for vulnerability.

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/or economic loss. Climate change can also cause or influence extreme weather events.

Greenhouse Gases
Natural or manmade gases that trap heat in the atmosphere and contribute to the greenhouse effect. The primary GHGs emitted by the transportation sector are carbon dioxide, nitrous oxide, methane, and hydrofluorocarbons.

Monte Carlo Method
A type of simulation that explicitly and quantitatively represents uncertainty by repeating an analysis using a large number of different values for its critical parameters obtained by drawing repeatedly from their underlying probability distributions. By doing so, it generates a probability distribution of possible outcomes that incorporates the combined uncertainty surrounding each of these parameters.

Radiative Forcing
A measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. It is used to assess and compare the anthropogenic and natural drivers of climate change.

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.

Risk
A combination of the likelihood that an asset will experience a particular climate impact, and the severity or consequence of that impact.

Sensitivity
Refers to how an asset or system responds to, or is affected by, exposure to a climate change stressor. A highly sensitive asset will experience a large degree of impact if the climate varies even a small amount, where as a less sensitive asset could withstand high levels of climate variation before exhibiting any response.

Transportation Asset Management
A strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost.

Vulnerability
The degree to which a system is susceptible to, or unable to cope with adverse effects of climate change or extreme weather events. In the transportation context, climate change vulnerability is a function of a transportation system's exposure to climate effects, sensitivity to climate effects, and adaptive capacity.

Appendix C: Description of FHWA Climate Resilience Pilots

Pilot	Project Description	Illustrative Project Findings and Key Outcome
Arizona DOT (ADOT)	The ADOT team conducted a study to identify hotspots where highways are vulnerable to associated hazards from high temperatures, drought, and intense storms. The project focused on the Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff, which includes a variety of urban areas, landscapes, biotic communities, and climate zones and presents a range of weather conditions applicable to much of Arizona.	Because the study scope covered a 300-mile stretch of highway, it helped screen for areas that require a closer analysis of specific assets' vulnerabilities. The study found that while temperature increases may reduce winter maintenance and operations costs, extreme heat may also require a reevaluation of design standards for heat-resistant pavement and affect protocols for construction windows and worker safety. The assessment also found that future precipitation and wildfire trends are uncertain, though increases in the magnitude of events could pose a threat to ADOT assets.
California DOT (Caltrans) District 1	The vulnerability assessment approach drew from methodologies developed by FHWA and the Washington State DOT 2010–2011 climate resilience pilot project. The pilot assessed vulnerability in four counties by scoring asset criticality and potential impact. The pilot identified adaptation options at four prototype locations of vulnerable road segments. The Caltrans District 1 team formalized their adaptation methodology into a tool to assist with the evaluation and prioritization of adaptation options.	Climate change will predominately impact District 1 roads through sea level rise and increased coastal erosion hazards. Inland, the district is also vulnerable to significant historical slope instability, drainage, and erosion. The vulnerability assessment is informing studies on Highway 101 and the adaptation analysis is providing information to assist a local transportation planning agency in its assessment of routing options over a river.
Capital Area MPO (CAMPO) and the City of Austin, Texas	The CAMPO team used a data and stakeholder-driven approach to assess risks to nine critical assets from flooding, drought, extreme heat, wildfire, and ice. The project team conducted a criticality workshop, developed local climate projections, and performed risk assessments for each asset.	The project team conducted research and interviews to identify "sensitivity thresholds" for each stressor—that is, the levels of rain or temperature at which the region's transportation infrastructure experiences disruptions or damage. These thresholds helped identify what climate data to develop and how to apply the climate data in a vulnerability assessment. CAMPO also used a regional climate model (RCM) rather than downscaled global climate models. CAMPO incorporated the results of the study into their latest LRTP. At the conclusion of the study, CAMPO and the city of Austin hosted an inaugural Extreme Weather Resiliency Symposium with agencies from around the region, and intend to form a multi-agency working group to build on the momentum of this project.
Connecticut DOT (CTDOT)	The CTDOT team conducted a systems-level vulnerability assessment of bridge and culvert structures from inland flooding associated with extreme rainfall events. The assessment included data collection and field review, hydrologic and hydraulic evaluation, criticality assessment and hydraulic design criteria evaluation.	The CTDOT team found that most structures were built with excess capacity and will therefore be able to accommodate future increases in precipitation. Moving forward, CTDOT recommended that all new infrastructure be designed using the precipitation data from the NRCC-NRCS "Precip.net" until the new NOAA Atlas 14 data were available. Before this study, CTDOT was still using TP-40 for their designs which hadn't been updated since 1961.
Hillsborough MPO, Florida	The Hillsborough MPO team assessed the vulnerability of select surface transportation assets to sea level rise, storm surge, and flooding in order to identify cost-effective risk management strategies for incorporation into short-term and long-range transportation planning.	The Hillsborough MPO devoted a chapter within its Long-Range Transportation Plan (LRTP) to discuss the results of this analysis. One of the assets identified as critical in the study was scheduled for reconstruction in the MPO's LRTP and the MPO found that adaptation measures could be incorporated cost-effectively during reconstruction. For example, a $4.2 million investment to mitigate flood risk for Memorial Highway would result in a net benefit of $2.1-$8.4 million if it experienced a Category 1 storm surge (and higher benefits for a stronger storm).

Pilot	Project Description	Illustrative Project Findings and Key Outcome
Iowa DOT	To evaluate future flood conditions, the Iowa DOT team developed a methodology to integrate climate projections of rainfall within a river system model to predict river flood response to climate change. Iowa DOT tested this methodology in two river basins to evaluate the strengths and weaknesses of technology to produce scenarios of future flood conditions. They also analyzed the potential impact of the future floods on six bridges to evaluate vulnerability to climate change and extreme weather and inform the development of adaptation options.	Iowa DOT determined that the leading edge of downscaled climate projection data resolution (one-eighth degree and daily increments) was sufficient for simulating peak flow statistics of "Big Basins and Big Floods," quantitatively defined as basins exceeding 100 square miles with floods exceeding twice the mean annual peak flow. This modeling was used to confirm that a new bridge project on I-35 will be resilient under future flood scenarios.
Maine DOT	The Maine DOT team identified transportation assets that are vulnerable to flooding from sea level rise and storm surge in six coastal towns. The team developed depth-damage functions and adaptation design options at three of the sites and evaluated the costs and benefits of the alternative design structures.	The analysis found that the majority of damage would be from storm surge, not sea level rise. At each site, they identified the design option with the lowest total life cycle cost under each sea level rise scenario. In general, smaller structures that required lower or moderate initial construction costs tended to be more cost-efficient.
Maryland State Highway Administratio (SHA)	The Maryland SHA team developed a three-tiered vulnerability assessment methodology and GIS layers of statewide water surfaces to analyze vulnerability to sea level rise, storm surge, and flooding in two counties. The team also reviewed design strategies, best management practices, planning standards, and other ways to support the adoption of adaptive management solutions.	The sea level rise mapping results have been integrated into the project screening process. Additionally, Maryland SHA is using the results in their regional planning processes, such as when the Office of Structures staff are doing a bridge replacement, they will see the vulnerability assessment results. SHA will evaluate the vulnerability of drainage structures Statewide using the approach developed in the pilot.
Massachusetts DOT (MassDOT)	The MassDOT team sought to better understand the vulnerability of the I-93 Central Artery/Tunnel system (CA/T) in Boston to sea level rise and extreme storm events. The team combined a state-of-the-art hydrodynamic flood model with agency-driven knowledge and priorities to assess vulnerabilities and develop adaptation strategies.	The project team used the model to develop a series of projected water surface elevations for hurricanes and nor'easters. Using a Monte Carlo approach, the team was able to estimate the probability of flooding on a high-resolution grid under current and two future sea level rise scenarios, and to assess flood entry points and pathways (and thereby identify potential locations for regional adaptation strategies). In many cases, large upland areas are flooded by a relatively small and distinct entry point (e.g., a low elevation area along the coastline).
Michigan DOT (MDOT)	The MDOT team conducted a climate-based vulnerability assessment of mostly MDOT-owned and -operated transportation infrastructure, including roads, bridges, pumps and culverts. The assessment used GIS to overlay climate projections onto asset information from MDOT's existing asset management database to help identify locations and infrastructure that may be at risk.	The assessment found that the most at-risk transportation assets were situated in the southern third of the State, where the State's larger urban areas are located. Increased winter temperatures and precipitation could result in decreased snowfall and increased rain, posing potential operations and maintenance challenges. The analysis also revealed that additional data on elevation, flood plains, and land use would be helpful to provide a more robust assessment of asset vulnerability.
Minnesota DOT (MnDOT)	The MnDOT team conducted a vulnerability assessment of bridges, culverts, pipes, and roads paralleling streams to flooding in two districts. Based on the vulnerability assessment results, they developed facility-level adaptation options for two selected culverts programmed for replacement. Using damage and economic loss estimates associated with flash flooding as well as cost estimates for alternative engineering designs the team identified the most cost-effective options under a range of climate scenarios.	MnDOT plans to incorporate the identified risks into culvert and bridge improvement programs, asset management databases, the asset management plan, and MnDOT's risk registers. This information may feed into the development of emergency action plans, real-time monitoring and warning systems for vulnerable assets, and the prioritization of funding for cost-effective adaptation strategies.

Pilot	Project Description	Illustrative Project Findings and Key Outcome
Metropolitan Transportation Commission (MTC)	The MTC team refined its first pilot vulnerability assessment (2010–2011 FHWA pilot program) with additional sea level rise mapping and hydraulic analysis. Using the revised vulnerability data, the project team developed a comprehensive suite of adaptation strategies for three focus areas, and through a systematic evaluation process, they selected five adaptation strategies for further development: living levees (in two locations), an offshore breakwater, a drainage study, and mainstreaming climate change risk into transportation agencies planning processes.	The policy/research and physical adaptation strategies developed as part of this pilot all include information on the process and partners needed for implementation, preliminary scopes/conceptual designs (including cost estimates), potential barriers, and a summary of impacts of implementation. This information is helping to inform regional and State policy and investment decisions, and the overall process is serving as a framework for similar projects in the region.
North Central Texas Council of Governments (NCTCOG)	The NCTCOG team assessed the vulnerability of existing and planned transportation infrastructure in the Dallas-Fort Worth region, where extreme weather events will add an additional stress on the transportation system in the rapidly growing region.	The vulnerability assessment found that 636 miles of roads in the region have the potential to be inundated by a 100-year flood. The pilot project also found that the increase in temperature compounded by a projected decrease in annual rainfall in the region may reduce soil moisture, which could cause pavement cracking and stresses on bridges and culverts.
New Jersey DOT/North Jersey Transportation Planning Authority (NJTPA)—Coastal and Central New Jersey	The North Jersey Transportation Planning Authority (NJTPA) led the interagency NJ Partnership to assess the vulnerability of the State's transportation systems. Much of New Jersey's infrastructure is aging and concentrated near major rivers and the coast. The NJ Partnership wanted to understand how to make more strategic capital investments in light of the changing climate. To accomplish this goal, the project team conducted a Geographic Information System (GIS)-based climate vulnerability assessment on transportation assets in a Coastal Study Area along the Atlantic Ocean and in a Central Study Area, which includes six counties across the State that encompass a significant transit corridor.	The assessment found that the 1-in-100 year floodplain will expand under future climate conditions, with the greatest expansion occurring under the most severe scenario. This could be significant by 2050 and highly disruptive by 2100, with over 19 miles of critical roadway at risk of inundation. NJ TRANSIT indicated that temperatures higher than 95°F will increase the risk of rail kinks and that catenaries may sag or experience pulley failures during extreme heat. The Partnership study developed a series of matrices to identify potential adaptation strategies that could be implemented at the planning, design, and operations phases of transportation decisionmaking. The matrices also indicate whether impacts are expected to occur more or less frequently in the absence of adaptation.
New York State DOT (NYSDOT)	The NYSDOT team assessed the vulnerability of the transportation system to changes in precipitation in the rural Lake Champlain Basin. The team developed a benefits valuation approach to help decisionmakers prioritize infrastructure and assess when to undertake culvert replacements considering social, economic, and environmental factors. They evaluated vulnerability, criticality and risk, and developed a method to apply an environmental benefits multiplier to each culvert.	The approach considers qualitative and quantitative factors and provides a menu of potential benefits that users can tailor to different geographies and data availability. Overall, the results of the pilot project illuminated that a strong asset management strategy will focus funds on the right treatment at the right time in the right place. The strategy considers the condition of the assets, the location and the project's context in the transportation system and local geography, risk to the assets, and the function of the roadway.
Oahu MPO	Oahu MPO facilitated a workshop to identify and prioritize transportation assets that may be vulnerable to climate impacts. The study focused on five high-priority sites with existing vulnerability to extreme weather and climate variability. Oahu MPO developed a highly efficient "triage" approach that could be replicable both within the State and across the Pacific island nations. Prior to the workshop, Oahu MPO consulted climate scientists to develop a baseline understanding of the current climate change impacts affecting the islands. These discussions identified the key climate impacts of concern. Oahu MPO also consulted with lead planners and engineers to gather knowledge on Oahu's highways, harbors, and airports.	The study identified Honolulu Harbor, Honolulu International Airport, and Farrington Highway on the Waianae Coast as the three transportation asset groups with the highest integrated risk due to climate change. Overall, the project team found that warmer temperatures and increased wind speeds will not pose a large risk to transportation assets. The climate impacts of greatest concern are sea level rise, storm surge, and intense rainfall.

Pilot	Project Description	Illustrative Project Findings and Key Outcome
Oregon DOT (ODOT)	The ODOT team engaged maintenance and technical staff and utilized asset data to assess the vulnerability of highway infrastructure in two coastal counties to extreme weather events and higher sea levels. Based on the results of the vulnerability assessment, the pilot conducted further analysis of specific adaptation sites, options, and benefits and costs for five priority storm and landslide hazard areas. Options analyzed ranged from "do nothing" scenarios to options for increased operations and maintenance and options with significant construction and engineering requirements.	Nearly all the designated "Lifeline Routes" in the study area, which are essential for emergency response and economic connectivity, were found to be vulnerable to projected climate impacts. ODOT developed a list of adaptation options for highly vulnerable sites. However, they found that implementing adaptation strategies would not be cost-effective at the two sites they performed cost-benefit analyses for, due to availability of detour routes and low traffic volumes, and other factors. This suggests adaptation may be more appropriate at a corridor-level in Oregon. ODOT also identified many parallels between adaptation planning work and seismic resilience planning work, and is looking for ways to enhance that collaboration.
South Florida	The South Florida team focused on a four-county region in conducting a detailed geospatial analysis to calculate vulnerability scores for "regionally significant" road and passenger rail infrastructure. The study also recommended ways for partner agencies to incorporate the vulnerability results into their normal decisionmaking processes.	A key outcome of this study was a consolidated and quality-controlled geospatial dataset of the region's transportation infrastructure, elevation, and floodplains. The team learned that data availability and quality were critical to the data-driven analysis and identified several strategies to facilitate data collection and aggregation in future efforts, including encouraging the collection of relevant data a part of normal activities.
Tennessee DOT (TDOT)	The TDOT team conducted an extreme weather vulnerability assessment of transportation infrastructure across the State. The project team compiled a statewide inventory of the most critical transportation infrastructure and used historical and projected climate and weather data as well as stakeholder feedback to develop rankings of the vulnerability of critical transportation assets to projected temperature and precipitation changes and other extreme weather events.	The team found that climate impacts vary greatly across the State, with different events creating high levels of vulnerability in west, middle, and east Tennessee. TDOT intends to select 15–20 of the most vulnerable assets identified by the study for a more detailed analysis and initiate a dialogue on how to incorporate results from the study into TDOT and MPO policies and procedures across Tennessee. TDOT also plans to use the vulnerability assessment in developing a risk-based transportation asset management plan.
Virginia DOT—Hampton Roads	Hampton Roads, Virginia, is a low-lying, coastal metropolitan region that serves as the site for multiple military installations, including the largest naval base on the East Coast. This pilot study used an existing decision model to evaluate how the transportation priorities of the region might be influenced by a variety of climate change, economic, regulatory, travel-demand, wear-and-tear, environmental, and technology scenarios.	The pilot found that the most influential scenario for priority-setting was a combination of sea level rise and storm surge with increased traffic demand (see Figure 3). This scenario significantly disrupted existing priorities for projects, assets, TAZs, and policies. Interestingly, prioritization of planned projects was most sensitive to the climate-change-only scenario. The decision model is available as an Excel workbook tool that guides users through the process of identifying assets, selecting criteria, building a base case, and developing climate and climate-plus scenarios.
Washington State DOT (WSDOT)	The WSDOT team examined adaptation options in the Skagit River Basin, an area of the State identified as highly vulnerable to flooding during the FHWA 2010–2011 pilot study assessment. Adaptation options centered on 11 vulnerable road segments in the study area. Options included active traffic management, detour routes, basin-wide flood easements, and culvert improvements.	The WSDOT team explored using a then-in-process U.S. Army Corps of Engineers flood study of the Skagit River Basin to understand vulnerabilities, identify adaptation strategies, and foster interagency collaboration. The team found that this model-based analysis validated and complemented their earlier workshop and interview-based analysis and that it is critical to communicate proposed actions between agencies.
Western Federal Lands Highway Division (WFLHD) and the Alaska DOT and Public Facilities (ADOT&PF)	The WFLHD/ADOT&PF team assessed three unique climate change issues in the State of Alaska. In Kivalina, the pilot considered the impact of the loss of sea ice, sea level rise, and wind on shoreline erosion of the coastal runway. In Igloo Creek and along the Dalton Highway, the pilot considered the impacts of increased temperature (resulting in permafrost melt) and increased precipitation on landslides and pavement cracking.	In addition to looking at primary variables such as temperature and precipitation, the WFLHD/ADOT&PF team considered it important to also consider secondary and tertiary variables, such as permafrost thaw and landslides, respectively.

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