DEPARTMENT OF TRANSPORTATION

Transportation Research Synthesis

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DEVELOPING TRANSPORTATION SYSTEM CLIMATE RESILIENCE PERFORMANCE MEASURES

Prepared by CTC & Associates LLC

Climate change is exacerbating weather-related impacts on the transportation system. As floods, droughts, wildfires and other extreme weather events become more common and destructive, transportation infrastructure will need to adapt to become more resilient.

To better understand how climate change will impact Minnesota's transportation system and to identify areas of high risk in the state, MnDOT is seeking to develop a new strategy that measures and tracks a range of climate resiliency-related variables. This Transportation Research Synthesis presents the findings of a survey of state transportation agencies about the performance measures and practices implemented to monitor the agencies' climate resilience efforts. Supplementing these findings are case studies of selected state departments of transportation and resources obtained through a literature search.

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Developing Transportation System Climate Resilience Performance Measures

Introduction

The increasing risks of climate change to transportation systems require strategic resilience planning and implementation. In Minnesota, the impacts of climate change are already affecting the state's transportation system, but the extent of the potential repercussions is not yet well understood. To gain a more thorough understanding of these impacts, MnDOT is undertaking a strategic approach to measuring and tracking how climate change is affecting the state's transportation system, including the development of climate resilience performance measures.

MnDOT has approached performance measure development in the context of the new federal program Promoting Resilient Operations for Transformative, Efficient and Cost-Saving Transportation (PROTECT), a provision of the 2021 Infrastructure Investment and Jobs Act. To inform the development of these measures, the agency is seeking information about the practical tools and procedures used by other state departments of transportation (DOTs) to track and measure the impacts of climate change on the performance of the transportation systems that they manage. Specifically, MnDOT is interested in identifying the:

- Climate-related resiliency database or suite of databases that these state DOTs and other organizations are using, or if they only track measures qualitatively.
- Performance measures that are tracked and whether they include design, construction and maintenance costs related to increasing climate resilience.
- Workflows employed to track and use these measures.

This Transportation Research Synthesis presents the findings of efforts to gather this information, including a survey of state transportation agencies, follow-up consultations with representatives from selected state DOTs that have developed or are developing climate resilience performance measures, and a limited literature search of domestic resources.

Summary of Findings

Survey of Practice

An online survey was distributed to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Transportation System Security and Resilience. Transportation agencies from 12 states participated in the survey: Alaska, Arizona, Delaware, Georgia, Hawaii, Kansas, Kentucky, Michigan, Rhode Island, Utah, Washington and Wyoming.

Of these agencies:

- One agency—Arizona DOT—has developed and is using climate resilience performance measures to monitor flooding, extreme precipitation events and increasing temperature.
- Nine agencies—Delaware, Georgia, Hawaii, Michigan, Rhode Island, Utah and Washington State DOTs; Alaska DOT and Public Facilities; and Kentucky Transportation Cabinet—are developing performance measures or hope to develop them soon.

- Two agencies—Kansas and Wyoming DOTs—have not developed performance measures and have no plans to develop them.

Survey results are summarized in two topic areas:

- Performance measures currently in place.
- Performance measures under development.

Performance Measures Currently in Practice

Arizona DOT has created a formal Resilience Program to address the impacts of extreme weather and changing climate trends. The agency uses performance measures to move the Resilience Program from a qualitative to quantitative approach. The survey respondent reported on the agency's use of performance measures in three areas:

- **Flooding.** The number of U.S. Geological Survey (USGS) flood assessment assignments completed is used as a performance measure. In a follow-up conversation, the Arizona DOT survey participant noted that through a partnership with Arizona DOT, the USGS performs modeling and flood analysis during or after a flood event in the state, usually between six and 10 times per year. These assessments vary in complexity, from a simple desktop review of data collected by instruments already in place to a full on-site instrumentation. The assessments help Arizona DOT build its cache of historical hydrologic data and improve its understanding of how floods interact with the state's infrastructure. With this insight, Arizona DOT is able to link system flooding hot spots with scoping efforts for new projects.

- **Extreme precipitation events**. The number of natural hazard engineering assessments completed is used as a performance measure. Decision-making is then based on scientific evidence in engineering design. Data is sourced through natural hazard root cause and climate model analysis. Methodologies include the U.S. DOT Coupled Model Intercomparison Project (CMIP) Climate Data Processing tool; guidance from NCHRP 15-61, Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure; an internal end-to-end engineering process; and Arizona DOT's Climate Engineering Assessment for Transportation Assets (CEA-TA) process.

- **Increasing temperature**. The number of pavement segments and climate data pilot projects is used as performance measures. The agency uses the CMIP tool to obtain data and has developed advanced pavement design guidance that considers future heat on binder grade and freeze-thaw locations. The survey respondent noted that Arizona DOT also participates in Transportation Pooled Fund TPF-5(478), Demonstration to Advance New Pavement Technologies.

Data Collection Practices

Arizona DOT uses ArcGIS tools and spreadsheets to track climate resilience performance measures. Through its partnership with the USGS, the agency is also able to use data stored on the ScienceBase and Earth Resources Observation and Science (EROS) databases. Data is stored in an in-house database and an internal dashboard.

The respondent noted that the agency has not encountered challenges in developing and tracking climate resilience performance measures.

Performance Measures Under Development

Three survey respondents described their agencies' efforts to develop performance measures:

- *Michigan DOT* is logging flooding events in the Detroit metropolitan area. Most of these events are tied to pump station failures, typically as a result of power outages. The agency plans to develop software that incorporates weather data and elevation to allow staff to anticipate and mitigate issues with subsequent performance data.
- *Rhode Island DOT* has developed STORMTOOLS to measure sea level rise. The tool is built on an ArcGIS platform and is used in an asset management based decision matrix for project planning. The tool is available to the public, allowing state residents to understand their risk of coastal flooding. Rhode Island DOT may also establish greenhouse gas (GHG) performance measures for the state Action on Climate goals.
- *Utah DOT* has identified many threat asset pairs and has developed a risk map of pavement, bridge and culvert assets. Information from completed projects is used to change the risk/resiliency profile of assets.

Five survey respondents described their agencies' preliminary efforts to develop performance measures:

- *Alaska DOT and Public Facilities* has established a resilience team that is considering performance measures as part of its selection criteria.
- *Delaware DOT's* Transportation Resiliency and Sustainability division, initiated less than a year ago, will consider performance measures to gauge progress.
- *Georgia DOT* has created a resiliency committee with a core focus on mitigation, resilience, repetitive loss identification and grants management. Goals for the next year include establishing and implementing an overall strategy.
- *Kentucky Transportation Cabinet* is currently developing and implementing performance measures.
- *Washington State DOT* is adding resilience to its strategic plan and asset management plans (expected completion: summer 2022) and will likely develop performance measures in the future. The agency is also evaluating the requirements of new federal and state legislation, which may inform resilience and equity performance measures, including the state's Climate Commitment Act, which establishes a comprehensive program to reduce carbon pollution and achieve the state GHG limits, and the Healthy Environment for All (HEAL) Act, which aims to eliminate environmental and health disparities among communities of color and low-income households.

Case Studies

To better understand other agencies' climate change resiliency efforts, researchers conducted follow-up consultations with the respondents from Arizona DOT and Utah DOT, and contacted Colorado DOT for information about its resilience program. Findings from these consultations are presented below.

Arizona

Arizona DOT's Resilience Program is the result of the agency's formal climate resiliency efforts launched in 2015. To account for current and future infrastructure risks, the agency began to develop a new end-to-end engineering approach for managing risk and long-term asset management strategies. The CEA-TA incorporates extreme weather and climate adaptation into the design engineering, asset management and life cycle planning processes, and is used to identify the transportation infrastructure's most urgent climate-related threats, including intense precipitation, system flooding, wildfires, wildfire-induced floods, drought-related dust storms, rockfall incidents, slope failures and increased surface temperatures. The agency has launched a pilot project to address these stressors through the life cycle planning of roadway assets and asset classes.

Data Collection

Data obtained through its partnership with USGS, particularly hydrologic data, is used to assess and mitigate potential risks and to inform design and management decisions related to the state's highways, bridges and other infrastructure. The partnership also enables Arizona DOT to use data stored on the ScienceBase and Earth Resources Observation and Science (EROS) databases.

Two data collection projects are currently underway: the Laguna Creek Bridge Scour Remediation pilot project, which is testing a suite of USGS next generation technologies for use in evaluating transportation infrastructure, and the San Pedro River at St. David and the Gila River at Florence, a three-year project that will provide critical data to monitor the magnitude of floods, refine hydrologic models and better understand how channel conditions change over time.

Tools and Other Resources

Arizona DOT has also created tools to analyze resilience in pavements, highway stormwater pumps and bridges. Among these tools is the CMIP tool, which processes climate output that planners can use to consider design or operational changes needed to create resilient transportation infrastructure and services. Additional guidance is obtained from NCHRP Project 15-61, Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure, which produced design practices for hydraulic engineers to address the impacts of climate change. Agency participation in Transportation Pooled Fund TPF-5(478), Demonstration to Advance New Pavement Technologies, also benefits the agency's resiliency efforts. This project seeks to identify asphalt and concrete paving advancements and implemented effective strategies for rapid deployment of new and promising technologies. Among the goals of this project are to integrate sustainability and resiliency into the decision-making process, technical frameworks, education efforts and stakeholder engagement of pavement technology.

Lessons Learned

The survey respondent recommended the following steps for developing a climate-responsive infrastructure program:

- Form and use an agency internal working group.
- Look for partnerships outside the agency, including academia and research institutes.
- Create impact narratives for weather and natural hazard stresses for communicating the risk and need for mitigation steps.
- Establish financial decision-making steps for investment planning and providing a feedback loop.
- Track resilience-building steps, projects and priorities.
- Establish a comprehensive geographic information system (GIS) database to define risks and mitigation strategies.
- Assess measurable climate trends and probabilistic climate risk modeling from multiple sources.
- Ensure leadership direction.

Colorado

A series of natural and human-caused events, including devastating floods and wildfire, prompted Colorado DOT to establish a resilience program to assess the risks to its transportation system. The agency is guided by a state policy directive that requires the agency to incorporate resilience in strategic decisions about transportation assets and operations.

The I-70 Risk and Resilience Pilot, completed in late 2017, addressed the vulnerabilities in Colorado's highway infrastructure by quantifying the risk and developing mitigation measures. The pilot study examined 450 miles of Interstate 70 (I-70) and considered multiple significant threats, including avalanches and wildfire. The Risk and Resilience (R&R) for Highways Framework was produced from this research to assess transportation system performance under a range of potential physical hazards and to inform project selection and investment decisions, maintenance and operational procedures and the design process.

While Colorado DOT does not currently use climate resilience performance measures, a project launched in April 2022 aims to develop five performance measures. The agency also intends to develop proof-of-concept case studies that show how resilience can be incorporated in day-to-day project development.

Tools and Methodologies

Colorado DOT has developed a number of tools to adopt resiliency planning and to measure asset risk and resilience, including the following:

Resiliency Planning

- Resiliency Planning and Investments explains the impact of natural disasters and includes examples of Colorado DOT resilience investments.
- Changing Climate and Extreme Weather Impacts on Geohazards in Colorado (2021 Colorado DOT climate study) evaluates the impact of climate change induced weather patterns and extreme weather events on geologic hazards.
- Integrating Resiliency at Colorado DOT: Asset Management highlights a benefit-cost analysis of asset risk assessment.
- Integrating Resiliency at Colorado DOT: Project Prioritization presents a case study for developing a scoring tool that incorporates resiliency into a project's overall score and rating to justify additional funding for a project with added resiliency measures.

Risk Assessment

- Risk and Resilience Tool uses an Excel spreadsheet to develop benefit-cost ratios for assets based on threat type, the likelihood of the threat occurring, and the consequence to the owner and user.
- Asset Criticality Model for System Resilience describes the steps to determine asset criticality, which is the first step in the R&R for Highways process.
- 4R Framework for Identifying and Evaluating Resiliency in Transportation System Assets and Organizations describes aspects of resilient transportation assets and organizations based on robustness, redundancy, resourcefulness and rapidity.
- CDOT Detour Identification Tool describes an application of the statewide travel demand model that identifies an optimal detour route when road closures occur on the state highway system.
- CDOT Asset Resiliency Mapping Application identifies Colorado DOT assets and threats and the criticality of highway corridors.

Utah

Utah DOT's Asset Risk Management Process applies qualitative and quantitative analyses that build on the seven-step RAMCAP (Risk Analysis and Management for Critical Asset Protection) model. Using existing data and institutional knowledge, the agency is developing comprehensive resilience assessment procedures in connection with a group of natural hazards: avalanches and earthquakes (bridges only), rockfalls, floods and debris flows.

Models, Tools and Other Resources

The agency's adaptation of RAMCAP's risk and resilience assessment (Step 6) applies two equations:

- Equation 1 considers impact, probability and vulnerability to assess risk.
- Equation 2 assesses resiliency by considering the calculated risk, criticality and risk priority.

For Utah DOT, improvements to resiliency are associated with improvements in four resiliency measures—rapidity, resourcefulness, redundancy and robustness. The agency also analyzes threat asset pairs to assess the impact of different types of threats on selected asset classes (bridges (approaches, box culverts), culvert pipes and pavement). A return on investment calculation is used to prioritize risk.

Results of the agency's risk and resiliency analyses are reflected in the GIS-based Risk Priority Analysis tool and Risk Priority Analysis StoryMap, which the agency uses to leverage existing data to help stakeholders and decision-makers visualize the risks and threats to the state's infrastructure.

Related Research

Supplementing the survey results and follow-up consultations are publications and other resources sourced through a limited literature search. Findings from this search include a 2021 Transportation Research Board (TRB) special report that reviews transportation agency practices for evaluating resilience, a 2019 TRB journal article about critical issues in transportation related to climate change resilience and a 2015 Federal Highway Administration (FHWA) climate change adaptation guide. Additional resources are presented in the following categories:

- **Measuring and monitoring performance**, which includes a National Oceanic and Atmospheric Administration web resource that provides information and resources for measuring and tracking the climate resilience of transportation infrastructure. A number of state resources also provide indicators and design guidance for hazard-resilient infrastructure.
- **Tools and technology**, which includes resources about the RAMCAP Plus process that enhanced resilience efforts performed by Colorado DOT and Utah DOT. Also presented is Maine DOT's Facilitation Tool for tracking adaptation actions and Vermont DOT's Transportation Resilience Planning Tool (TRPT), which "estimates risk based on the vulnerability and criticality of roadway segments, and identifies potential mitigation measures based on the factors driving the vulnerability."
- **Risk assessment**, which highlights FHWA's Vulnerability Assessment and Adaptation Framework used to evaluate transportation system vulnerability. Also presented are several vulnerability assessment and adaptation pilot projects, sponsored by FHWA and conducted by state and regional agencies.
- **Adaptation priorities and costs**, which includes national and state resources that address the costs and benefits of adaptation measures for infrastructure resilience.

Next Steps

Going forward, MnDOT intends to:

- Share the results of the research synthesis broadly within the agency. The research synthesis findings will help inform future risk analysis and the development of new climate resilience performance measures for the state's transportation system.
- Leverage the findings from the research synthesis to strategically plan for new federal climate programs, including the PROTECT program.

Detailed Findings

Background

The increasing risks of climate change to transportation systems require strategic resilience planning and implementation. In Minnesota, the impacts of climate change are already affecting the state's transportation system, but the extent of the potential repercussions is not yet well understood. To gain a more thorough comprehension of these impacts, MnDOT is undertaking a strategic approach to measuring and tracking how climate change is affecting the state's transportation system, including the development of climate resilience performance measures.

To better evaluate overall transportation system resilience, MnDOT has approached performance measure development in the context of the new federal program Promoting Resilient Operations for Transformative, Efficient and Cost-Saving Transportation (PROTECT), a provision of the 2021 Infrastructure Investment and Jobs Act. PROTECT provides grants to support planning, resilience improvements, community resilience and evacuation routes, and at-risk coastal infrastructure. Currently, MnDOT is reviewing the following measures:

Tracking

- Significant weather-related damage to infrastructure.
- Use of emergency relief funds for repair/rebuild.
- Bridge condition rating.
- Bridges with scour plan of action.
- Culvert condition rating.

Existing, But Not Tracked with Resilience

- Pavement condition rating.
- Slope vulnerability rating.

Partially Existing, But Not Tracked with Resilience

- Bridge overtopping location and frequency.

Not Currently Tracked

- Pavement performance during extreme heat.
- Wildlife-upgraded culverts (aquatic organism passage).
- Slope failure location and frequency.
- Minor flood damage (under $5,000) location and frequency.
- Frequency and cost of mobilization and debris removal.
- Weather-related construction delays and damages.
- Resilience upgrades (such as slope armoring and raising roadways).
- Road closure location and frequency (when weather related).
- Green infrastructure (number, acres, etc.).
- Installation of green infrastructure (acres, total dollars or projects).
- Conveyance failures.
- Stormwater facility failures.
- Asset vulnerability to projected precipitation events (under development).

To inform the development of climate resilience performance measures, MnDOT is seeking information about the practical tools and procedures used by other state departments of transportation (DOTs) to track and measure the impacts of climate change on the performance of the transportation systems that they manage. Specifically, MnDOT is interested in identifying the:

- Climate-related resiliency database or suite of databases that these state DOTs and other organizations are using, or if they only track measures qualitatively.
- Performance measures that are tracked and whether they include design, construction and maintenance costs related to increasing climate resilience.
- Workflows employed to track and use these measures.

This Transportation Research Synthesis presents the findings of efforts to gather this information, including a survey of state transportation agencies, follow-up consultations with representatives from selected state DOTs that have developed or are developing climate resilience performance measures, and a literature search of domestic resources.

Survey of Practice

Survey Approach

An online survey was distributed to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Transportation System Security and Resilience. This committee's membership is national in scope and includes representatives from state DOTs in all 50 states and the District of Columbia. Survey questions are provided in Appendix A. The full text of survey responses is provided in a supplement to this report. Appendix B provides the contact information for survey respondents.

Twelve state transportation agencies participated in the survey:

- Alaska.
- Arizona.
- Delaware.
- Georgia.
- Hawaii.
- Kansas.
- Kentucky.
- Michigan.
- Rhode Island.
- Utah.
- Washington.
- Wyoming.

Of these agencies:

- One agency—Arizona DOT—has developed and is using climate resilience performance measures to monitor flooding, extreme precipitation events and increasing temperature.
- Nine agencies—Delaware, Georgia, Hawaii, Michigan, Rhode Island, Utah and Washington State DOTs; Alaska DOT and Public Facilities; and Kentucky Transportation Cabinet—are developing performance measures or hope to develop them soon.
- Two agencies—Kansas and Wyoming DOTs—have not developed performance measures and have no plans to develop them.

Summary of Survey Results

Below is a discussion of survey results in the following topic areas:

- Performance measures currently in place.
- Performance measures under development.

Performance Measures Currently in Place

Arizona

In the survey, the Arizona DOT respondent reported on the agency's use of performance measures or metrics in three areas: flooding, extreme precipitation events and increasing temperature. For most measures, the respondent provided target values, data sources and methodologies (such as assumptions, standards and calculations). Details about tracking intervals to evaluate performance (such as quarterly, annually or continuously) were not reported. Below is a summary of these measures. Additional information about Arizona DOT's resilience program and its climate change resilience efforts is presented in the **Case Studies** section of this report (page 13).

Flooding

Performance Measure	Number of U.S. Geological Survey (USGS) flood assessment assignments completed. *Note*: In a follow-up conversation, the Arizona DOT survey participant noted that through a partnership with Arizona DOT, the USGS performs modeling and flood analysis during or after a flood event in the state, usually between six and 10 times per year. These assessments vary in complexity, from a simple desktop review of data collected by instruments already in place to a full on-site instrumentation. The assessments help Arizona DOT build its cache of historical hydrologic data and improve its understanding of how floods interact with the state's infrastructure.
Target Values	Link system flooding hot spots with scoping efforts for new projects.
Data Sources	ADOT USGS Partnership (see **Case Studies**, page 13).
Methodologies	Not available.

Extreme Precipitation

Performance Measure	Number of natural hazard engineering assessments completed.
Target Values	Use decision-making based on scientific evidence in engineering design.
Data Sources	Natural hazard root cause and climate model analysis.
Methodologies	• U.S. DOT Coupled Model Intercomparison Project (CMIP) Climate Data Processing tool (see **Case Studies**, page 14). • NCHRP 15-61, Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (see **Case Studies**, page 14). • Internal end-to-end engineering process. • Arizona DOT Climate Engineering Assessment for Transportation Assets (CEA-TA) process (see **Case Studies**, page 13).

Increasing Temperature

Performance Measure	Number of pavement segments and climate data pilot projects.
Target Values	Develop advanced pavement design guidance that considers future heat on binder grade and freeze-thaw locations.
Data Sources	CMIP
Methodologies	Participation in Transportation Pooled Fund TPF-5(478), Demonstration to Advance New Pavement Technologies (see **Case Studies**, page 14).

Data Collection Practices

Arizona DOT uses ArcGIS tools and spreadsheets to track climate resilience performance measures. Through its partnership with the USGS, the agency is also able to use data stored on the ScienceBase and Earth Resources Observation and Science (EROS) databases. (See **Case Studies**, page 14, for more information about these databases and Arizona DOT's partnership with USGS.) Data is stored in an in-house database and an internal dashboard.

Performance measures are used within the agency to move Arizona DOT's Resilience Program from a qualitative to quantitative approach. (See **Case Studies**, page 13, for more information about Arizona DOT's resilience program.) The respondent noted that the agency has not encountered challenges in developing and tracking climate resilience performance measures, encouraging other agencies to "just develop the measures and do it."

Performance Measures Under Development

Three state DOTs responding to the survey are currently developing performance measures:

- *Michigan DOT* is currently logging flooding events in the Detroit metropolitan area. Most of these events are tied to pump station failures, typically as a result of power outages. The agency plans to develop software that incorporates weather data and elevation to allow staff to anticipate and mitigate issues, with subsequent performance data. (See ***Related Resource*** below for a similar effort conducted by the Southeast Michigan Council of Governments.)
- The *Rhode Island DOT* respondent provided information about two efforts:
    - STORMTOOLS was developed to measure sea level rise. Built on an ArcGIS platform, the tool is used by the agency in an asset management based decision matrix for project planning. The tool is available to the public, allowing state residents to understand their risk of coastal flooding. A smartphone app, the STORMTOOLS Risk and Damage Assessment App, is also available "to assist property owners, state agencies, permit applicants, municipal planners, industry users and the public to view storm risk and damage assessment information on maps for Rhode Island coastal properties."
    - Greenhouse gas (GHG) performance measures are also being considered for the state's Action on Climate goals.
- *Utah DOT* has identified many threat asset pairs and has developed a risk map of pavement, bridge and culvert assets. As the agency completes projects, it is using this information to change the risk/resiliency profile of the assets. (See **Case Studies**, page 19, for more information about Utah DOT's risk management efforts.)

Respondents from five agencies described the preliminary efforts underway within their organizations:

- *Alaska DOT and Public Facilities* has a resilience team that is considering performance measures as part of its selection criteria.
- *Delaware DOT's* Transportation Resiliency and Sustainability division was initiated less than a year ago. Division staff understands that performance measures will be needed to gauge progress.
- *Georgia DOT* has created a resiliency committee with a core focus on mitigation, resilience, repetitive loss identification and grants management. The committee anticipates establishing an overall strategy and implementation within the next year.
- *Kentucky Transportation Cabinet* is currently developing and implementing performance measures to better gauge the effects and costs climate change is having on its transportation assets.
- *Washington State DOT* is currently adding resilience to the agency's strategic plan and asset management plans (expected completion: summer 2022). The agency has not developed climate resilience performance measures but will likely develop them in the future (expected completion: unknown).

  The respondent added that the agency is evaluating the requirements of new federal and state legislation and orders, which may inform resilience and equity performance measures. State laws under review include the Climate Commitment Act, which establishes a comprehensive program to reduce carbon pollution and achieve the state GHG limits, and the Healthy Environment for All (HEAL) Act, which aims to eliminate environmental and health disparities among communities of color and low-income households.

Related Resource

Michigan

Climate Resiliency and Flooding Mitigation Study, Southeast Michigan Council of Governments, August 2020.
https://semcog.org/Portals/0/Documents/Plans-For-The-Region/Environment/SEMCOG%20Climate%20Resiliency%20and%20Flooding%20Mitigation%20Study_Report_August%202020.pdf?ver=pjn6fTnLv9BZaM8MuasqVw%3d%3d
From the abstract:

> The Southeast Michigan Council of Governments (SEMCOG) and Michigan Department of Transportation (MDOT) partnered to complete this study to assess flooding risk for roads, bridges, culverts and pump stations in the SEMCOG region. As severe flooding events persist and potentially worsen into the future, SEMCOG and MDOT seek to further understand vulnerabilities and best practices to address these challenges. This information will then be used to strategically guide planning and investment decisions in the continued safe and efficient operation of a resilient transportation network. This report outlines the methodology and results of the risk assessment and proposes a series of integration strategies to incorporate the flooding risk information into decision-making processes.

The metropolitan planning organization (MPO) developed the Flooding Risk Tool that can be used in regional transportation planning processes. The tool calculates flooding risk for roads, bridges, culverts and pump stations. The MPO is also considering developing flooding risk performance measures, such as:

- Percent of projects incorporating enhanced features to increase flooding resiliency.
- Number of "choke point" culverts.

Case Studies

To supplement the survey results, follow-up consultations were conducted with the respondents from Arizona DOT and Utah DOT to better understand their agencies' climate change resiliency efforts. In addition, researchers contacted Colorado DOT for information about a research project initiated in April 2022 to develop five new performance measures. Findings from these consultations are presented below.

Arizona Department of Transportation

Contact: Steven Olmsted, 602-524-7013, SOlmsted@azdot.gov

Background

To address weather events and natural hazards, including extreme weather and changing climate trends, Arizona DOT has developed a formal Resilience Program, which uses a programmatic approach that combines risk, science, technology and engineering to further understand the impacts of weather-related risks to the state's transportation system. The program is the result of the agency's formal climate resiliency efforts launched in 2015 when it noted the challenge to "[c]ontinue considering the balance between predictable asset deterioration curves, the sudden and unpredictable nature of extreme weather events and long-term climate trends, new models for risk assessment and lifecycle cost analysis, and appropriate adaptation strategies."

To account for current and future risks, the agency began to develop a new end-to-end engineering approach for managing risk and long-term asset management strategies. The Climate Engineering Assessment for Transportation Assets (CEA-TA) incorporates extreme weather and climate adaptation into the design engineering, asset management and life cycle planning processes. Arizona DOT has used this approach to identify the most urgent climate-related threats to the state's transportation infrastructure, including:

- Intense precipitation.
- System flooding.
- Wildfires.
- Wildfire-induced floods.
- Drought-related dust storms.
- Rockfall incidents.
- Slope failures.
- Increased surface temperatures.

A pilot project was "part of an ongoing work program through which ADOT plans to address [these] stressors through the life cycle planning of roadway assets and asset classes." (See **Related Resources** below for details about the pilot project.)

Data Collection

Through its partnership with the USGS, Arizona DOT seeks to promote "evidence-driven scientific decision-making" and use risk, science, technology and engineering to improve the agency's understanding of water-related data collection and natural hazard and weather-related risks to the state's transportation system. According to the agency website, the partnership has participated in more than 60 projects since 2014 and is "seamlessly linked" with Arizona DOT's Resilience Program, particularly in matters related to intense precipitation and system flooding, two stressors that pose the greatest threat to the state's transportation system.

Data obtained through this partnership, particularly hydrologic data, is used to assess and mitigate potential risks and to inform design and management decisions related to the state's highways, bridges and other infrastructure.

The affiliation with USGS also enables Arizona DOT to use data stored on the ScienceBase and Earth Resources Observation and Science (EROS) databases. Users can access complete water data sets, GPS and total station survey data housed in ScienceBase. EROS creates and stores metadata for all drone-derived projects on USGS servers for viewing and downloading.

Two projects are currently underway:

- The Laguna Creek Bridge Scour Remediation pilot project, a scour remediation project to address different types of water exposure on the state's highway system. A suite of USGS next generation technologies — including lidar, unmanned aircraft systems (UAS, or drones), Rapid Deployment Streamgage, noncontact velocity sensors, video camera and particle tracking data collection, 3D land surface models, scour chains, direct/indirect measurement of discharge, velocity vector analysis, erosion change mapping, flow sensors, UAS/unmanned aerial vehicle (UAV) surveying, terrestrial lidar, and 2D and 3D visualization tools — will be tested as they relate to transportation infrastructure.
- San Pedro River at St. David and the Gila River at Florence, a three-year project that will provide critical data for managing infrastructure. Researchers will collect and publish stage, discharge, velocity, water-surface profile and land surface data to better understand the hydrologic and hydraulic conditions at these two critical infrastructure locations. Arizona DOT will use the data to monitor the magnitude of floods, refine hydrologic models and better understand how channel conditions change over time.

Tools and Other Resources

Arizona DOT has also created tools to analyze resilience in pavements, highway stormwater pumps and bridges. Among these tools is the Climate Data Processing (CMIP) tool from the U.S. DOT Coupled Model Intercomparison Project. This tool "process[es] readily available downscaled climate projections at the local level into relevant statistics for transportation planners." Available in an Excel format, the tool processes climate output that planners can use to consider design or operational changes needed to create resilient transportation infrastructure and services.

The survey respondent added that the agency follows guidance developed under NCHRP 15-61, Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure. This project produced design practices for hydraulic engineers to address the impacts of climate change.

According to the survey respondent, the agency also participates in Transportation Pooled Fund TPF-5(478), Demonstration to Advance New Pavement Technologies. This project seeks to identify asphalt and concrete paving advancements and implemented effective strategies for rapid deployment of new and promising technologies. Among the goals of this project are to integrate sustainability and resiliency into the decision-making process, technical frameworks, education efforts and stakeholder engagement of pavement technology.

Additional information about Arizona DOT's use of tools for analyzing resilient transportation systems is presented in **Related Resources** below.

Lessons Learned

Below are Arizona DOT's recommended steps for developing a climate-responsive infrastructure program:

- Form and use an agency internal working group.
- Look for partnerships outside the agency, including academia and research institutes.
- Create impact narratives for weather and natural hazard stresses for communicating the risk and need for mitigation steps.
- Establish financial decision-making steps for investment planning and providing a feedback loop.
- Track resilience-building steps, projects and priorities.
- Establish a comprehensive geographic information system (GIS) database to define risks and mitigation strategies.
- Assess measurable climate trends and probabilistic climate risk modeling from multiple sources.
- Ensure leadership direction.

Additional guidance for preparedness and resilience to climate change and extreme weather events is available in FHWA Order 5520, Transportation System Preparedness and Resilience to Climate Change and Extreme Weather, which helps agencies anticipate and prepare for change, adapt to changing conditions, and respond and recover from disruptions.

Related Resources

"Extreme Weather, Climate and Risk Modeling for Multidecadal Considerations in Asset Management,"
Steven Olmsted, *Transportation Research Circular E-C277*, February 2022.
https://onlinepubs.trb.org/onlinepubs/circulars/ec277.pdf
[Scroll to page 68 of the circular.]
A summary of Arizona DOT's efforts to establish "an efficient, scientifically inferred engineering risk assessment" is presented.

Measuring Resiliency — Tools for Analyzing Resilient Transportation Systems, Webinar, Transportation Research Board, March 2021.
https://onlinepubs.trb.org/onlinepubs/webinars/210318.pdf
Slides 6 through 41 highlight Arizona DOT's Resilience Program, which includes tools in the following categories:

- **Business case and communications** (Slides 6 through 12): Provide background and operations information about the program.
- **Investment decisions** (Slides 13 through 19): Present steps in resilience financial decision-making and investment economic analysis.
- **Asset management** (Slides 20 through 22): Address risk type, risk rating scale and agency action process.
- **Engineering** (Slides 23 through 30): Include CEA-TA, USGS partnership, GIS databases and post-construction processes.
- **Climate** (Slides 31 through 33): Include data selection, climate output metrics and modeling.
- **Transportation system management and operations** (Slides 34 through 36): Describe plans to develop a dynamic reliability analysis decision support tool to assess factors that contribute to pumping unit and station failure.

- **Future plans** (Slides 37 through 41): Include resilience GIS database event dashboards; climate adaptation analysis; and advancements in resilience tools for cost-benefit analysis, return on investment, risk thresholds, durability and rehabilitation.

Asset Management, Extreme Weather and Proxy Indicators Pilot Project, Arizona Department of Transportation, March 2020.
https://azdot.gov/sites/default/files/media/2020/03/ADOT-Asset-Management-Infrastructure-Resilience-Study-Report%20Final-2020.pdf
From the executive summary:

> This project builds on eight years of the Arizona Department of Transportation (ADOT) extreme weather management, climate adaptation and resiliency work. The project follows a risk-based management process to identify the stressors that pose the highest threat to ADOT's transportation system. The pilot project is part of an ongoing work program through which ADOT plans to address the following stressors through the lifecycle planning of roadway assets and asset classes:
>
> - Intense Precipitation
> - System Flooding
> - Wildfires
> - Wildfire-Induced Floods
> - Drought-Related Dust Storms
> - Rockfall Incidents
> - Slope Failures
> - Increased Surface Temperatures

A discussion of the CEA-TA approach begins on page 11 of the report (page 22 of the PDF).

Colorado Department of Transportation

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Background

Colorado DOT's resilience program grew out of the agency's need to assess risk to its transportation system in response to natural and human-caused events, including devastating floods and wildfire. The agency's efforts are guided by a 2018 policy directive that "directs CDOT [Colorado DOT] to support state resilience goals by incorporating resilience in strategic decisions about transportation assets and operations."

The I-70 Risk and Resilience Pilot, completed in late 2017, addressed the vulnerabilities in Colorado's highway infrastructure by quantifying the risk and developing mitigation measures. The pilot study, which included 450 miles of Interstate 70 (I-70), from the state's western border with Utah to its eastern border with Kansas, considered multiple significant threats, including avalanches and wildfire. The pilot produced the Risk and Resilience (R&R) for Highways Framework to "assist CDOT and other highway agencies to understand how its system will perform under a range of potential physical hazards, inform project selection and investment decisions, maintenance decisions, operational procedures, and the design process as to risk-reducing investments and actions."

Efforts in this pilot project grew out of the agency's experience with the RAMCAP Plus (Risk Analysis and Management for Critical Asset Protection Plus) framework (see **Related Research**, page 25), which was adopted in response to significant flooding in 2013.

While Colorado DOT does not currently use climate resilience performance measures, a project launched in April 2022 aims to develop five performance measures. The agency also intends to develop proof-of-concept case studies that show how resilience can be incorporated in day-to-day project development.

Resiliency Planning

Several resources related to Colorado DOT's resiliency planning efforts are available at the agency's website, including:

- Resiliency Planning summarizes Colorado DOT's resiliency planning efforts.
- Resiliency Planning and Investments explains the impact of natural disasters and includes examples of Colorado DOT resilience investments.
- Changing Climate and Extreme Weather Impacts on Geohazards in Colorado (2021 Colorado DOT climate study) evaluates the impact of climate change induced weather patterns and extreme weather events on geologic hazards.
- Resilience (an appendix in the 2045 Statewide Plan) describes the agency's resilience program and the use of resiliency in the transportation planning process.
- Colorado DOT Building Back Better and Smarter for a More Resilient Transportation System (Esri case study) features the I-70 Risk and Resilience Pilot.
- Integrating Resilience into Agency Operations: Colorado DOT presents a four-page Federal Highway Administration case study about Colorado DOT's efforts to incorporate resiliency in operations.
- Integrating Resiliency at Colorado DOT: Asset Management highlights a benefit-cost analysis of asset risk assessment.
- Integrating Resiliency at Colorado DOT: Project Prioritization presents a case study for developing a scoring tool that incorporates resiliency into a project's overall score and rating to justify additional funding for a project with added resiliency measures.

In addition, a publicly available ArcGIS StoryMap provides a user-friendly guide explaining the various infrastructure threats and the agency's priorities.

Tools and Other Resources

The agency has also developed a number of tools for measuring asset risk and resilience, as well as video tutorials for using them:

- Risk and Resilience Tool uses an Excel spreadsheet to develop benefit-cost ratios for assets based on threat type, the likelihood of the threat occurring, and the consequence to the owner and user.
- Asset Criticality Model for System Resilience describes the steps to determine asset criticality, which is the first step in the R&R for Highways process.

- Risk and Resiliency Project Scoring Tool promotes the resiliency mindset for managing public resources.
- 4R Framework for Identifying and Evaluating Resiliency in Transportation System Assets and Organizations describes aspects of resilient transportation assets and organizations based on robustness, redundancy, resourcefulness and rapidity.
- CDOT Detour Identification Tool describes an application of the statewide travel demand model that identifies an optimal detour route when road closures occur on the state highway system.
- CDOT Asset Resiliency Mapping Application identifies Colorado DOT assets and threats and the criticality of highway corridors.

Related Resources

Risk and Resilience Analysis Procedure: A Manual for Calculating Risk to CDOT Assets From Flooding, Rockfall and Fire Debris Flow, Colorado Department of Transportation, 2020.
https://www.codot.gov/programs/planning/assets/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf
From the introduction: The purpose of this guidance is to establish an approach for prioritizing highway assets considering applicable risks and to determine potential financial impacts to highway asset owners and their users from these threats. The approach provides methods for assessing criticality of the study location to overall CDOT [Colorado DOT] system resilience, cost estimating procedures for replacement of damaged assets from natural hazards, user impact procedures for estimating additional user travel time/distance due to natural hazards, vulnerability tables for a range of assets to a range of physical threats, and methods/sources to estimate threat probabilities of select natural hazards in Colorado.

2020 Colorado Resiliency Framework, State of Colorado, December 2020.
https://drive.google.com/file/d/1efF8j0JLAmAnxi8_U4jq75uEWTAKxrGm/view
Colorado developed a resiliency framework to "link resiliency to regenerative recovery, climate action and building a more equitable future." The framework explores risks and vulnerabilities across four themes: adapting to changing climate, understanding risks from natural and other hazards, addressing social inequities and unique community needs, and pursuing economic diversity and vibrancy. The framework provides strategies in six planning sectors, including infrastructure.

The Impact of Climate Change: Projected Adaptation Costs for Boulder County, Colorado, Boulder County Sustainability, April 2018.
https://assets.bouldercounty.org/wp-content/uploads/2018/04/resilient-analytics-report-impacts-of-climate-change-boulder-county-colorado.pdf
From the executive summary: The current study quantifies the potential impact on Boulder County over infrastructure, human and natural sectors to provide a broad understanding of the potential impact of climate change. The study incorporates multiple climate scenarios projections through 2050 to provide a range of possible outcomes and fiscal impacts. The cost projections reflect a comparison of the environment in which the infrastructure or natural environments have historically existed or in which they were designed to operate with the projected future environment. The generation of these cost estimates reflects engineering and design-based guidelines that focus on the physical impacts of climate factors on the infrastructure and natural assets.

Utah Department of Transportation

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Background

A series of pilot projects has helped Utah DOT develop a risk management process that incorporates a risk and resilience assessment to reduce asset risk and damage resulting from environmental events such as severe weather, flooding and earthquakes. The agency's Asset Risk Management Process applies a combination of qualitative and quantitative analysis that is based on FHWA guidance and builds on the RAMCAP model (see **Related Research**, page 25). Using existing data and institutional knowledge, Utah DOT is developing comprehensive resilience assessment procedures in connection with a group of natural hazards: avalanches and earthquakes (bridges only), rockfalls, floods and debris flows.

To supplement the resilience performance measure used in the RAMCAP model, Utah DOT is analyzing threat asset pairs[1] to examine the types of threats posed to each asset class. A return on investment ratio is used as a performance measure when comparing options for risk mitigation.

1 The threat asset pairs under review include:

- **Threats**: Earthquake, flood, debris flow, rockfall and avalanche.
- **Assets**: Bridges (approaches, box culverts), culvert pipes and pavement.

Models, Tools and Other Resources

A 2021 TRB Special Report described the RAMCAP model, developed by the ASME innovative Technologies Institute, LLC, as providing a "consistent way to evaluate risk across different types of assets and hazards." RAMCAP Plus is the current version of this risk and resilience model.

Patrick Cowley, Utah DOT's director of Transportation Performance Management, describes the seven-step RAMCAP process in a September 2020 presentation to the AASHTO 2020 Joint Policy Conference:

- **Step 1. Asset Characterization**: What assets exist, which are critical and what should be considered?
- **Step 2. Threat Characterization**: What threats and hazards should be considered?
- **Step 3. Consequence Analysis**: What happens to assets if a threat or hazard occurs? What are the expected asset losses, economic impacts and lives lost?
- **Step 4. Vulnerability Analysis**: What are the asset vulnerabilities that would allow a threat or hazard to result in expected consequences? How vulnerable is the asset to the identified threat?
- **Step 5. Threat Assessment**: What is the likelihood of the identified threat?
- **Step 6. Risk/Resilience Assessment**: What is the anticipated asset total risk and resilience?
    - Risk = Consequences x Vulnerability x Threat
    - Resilience = Service Outage x Vulnerability x Threat
- **Step 7. Risk/Resilience Management**: What options are there to reduce risk and increase resilience? What is the risk reduction? What is the economic analysis of mitigation alternatives?

The agency's adaptation of RAMCAP's risk and resilience assessment is presented below:

Risk = Impact x Probability x Vulnerability

Resiliency = $\frac{1}{\text{Risk x Criticality}} = \frac{1}{\text{Risk Priority}}$

Cowley notes that improvements to resilience can come from improvements in four resiliency component measures:

- **Rapidity**: Measured by user cost; measurable unit is the difference from standard response time. Associated with Risk in the above equation; reduces impact.
- **Resourcefulness**: Measured by user cost and tied to rapidity. Associated with Risk in the above equation; reduces impact and may also reduce Criticality.
- **Redundancy**: Set benchmark based on travel demand model redundancy; track yearly change in benchmark. Associated with Criticality in the above equation and may reduce it.
- **Robustness**: Hardening; inversely proportional to risk. Associated with Risk in the above equation; reduces vulnerability.

Further details of the agency's modeling practices are available in a June 2020 Utah DOT report. Appendix A of UDOT Asset Risk Management Process: Risk Integration Approach applies the agency's risk priority analysis methodology using threat data on flood, rockfall, avalanche, earthquake and debris flow risks.

Results of the agency's risk and resiliency analyses are also reflected in the GIS-based Risk Priority Analysis tool and Risk Priority Analysis StoryMap, which the agency uses to leverage existing data to help stakeholders and decision-makers visualize the risks and threats to the state's infrastructure.

Resilience Measures

TRB Special Report 340, Investing in Transportation Resilience: A Framework for Informed Choices, describes resilience measures established by Utah DOT in connection with the RAMCAP model using three factors: output measure, intermediate measure and input data. Table 1 summarizes these measures.

Table 1. Utah DOT Resilience Measures

Output Measure	Intermediate Measure	Input Data
Risk Value	Hazard probability	Flood probability Rockfall probability Avalanche probability Debris flow probability Earthquake probability
Risk Value	Consequences	Repair costs for Utah DOT Length of detours Hourly value of time Hourly vehicle operating costs
Risk Priority	Risk value	See above

Output Measure	Intermediate Measure	Input Data
Risk Priority	Criticality	Road network redundancy Average annual daily traffic Truck average daily traffic
Net Benefits of Resilience Improvements	Risk priority (see above) Costs of improvements	

Related Resources

"A Low-Cost, Flexible Process for Assessing Environmental Risks and Resilience of Assets," Patrick Cowley, *Transportation Research Circular E-C277*, February 2022.
https://onlinepubs.trb.org/onlinepubs/circulars/ec277.pdf
[Scroll to page 16 of the circular.]
This is a brief summary of the agency's approach to risk and resilience, including use of the RAMCAP model and development of a resiliency performance measure based on rapidity, resourcefulness, redundancy and robustness.

Environmental Risk to Assets: Enterprise Risk and Resiliency, Transportation Performance Management (TPM) Division, Utah Department of Transportation, undated.
https://www.udot.utah.gov/connect/about-us/technology-innovation/transportation-performance-management-division/enterprise-risk-resiliency/
This website provides an overview of the agency's approach to risk and resilience modeling.

"Resilience," Patrick Cowley, Utah Department of Transportation, *AASHTO 2020 Joint Policy Conference*, September 2020.
https://2020policyconference.transportation.org/wp-content/uploads/sites/64/2020/10/Technical-Session-on-Resilience-Patrick-Cowley.pdf
This presentation highlights the seven-step RAMCAP process and identifies the simplified threat asset pairs used in the agency's resilience assessment.

UDOT Asset Risk Management Process: Risk Integration Approach, Utah Department of Transportation, June 2020.
https://drive.google.com/file/d/1lCjChiEnEBqT8gAcaonIhJ8DRacwy0Lt/view
This publication describes Utah DOT's risk integration approach and offers detailed examples of how the methodology is applied.

Related Research

Below are citations from a limited literature search of completed and in-progress domestic research conducted within the last 10 years related to the metrics, performance measures and systems transportation agencies are currently using to track climate resilience. Findings from the literature search are presented in the following categories:

- General guidance.
- Measuring and monitoring performance.
- Tools and technology.
- Risk and vulnerability assessments.
- Adaptation priorities and costs.

Publications and resources may be further categorized as national, state or related resources.

General Guidance

TRB Special Report 340: Investing in Transportation Resilience: A Framework for Informed Choices, Committee on Transportation Resilience Metrics, 2021.
https://nap.nationalacademies.org/cart/download.cgi?record_id=26292
From the executive summary: This report reviews current practices by transportation agencies for evaluating resilience and conducting investment analysis for the purpose of restoring and adding resilience. These practices require methods for measuring the resilience of the existing transportation system and for evaluating and prioritizing options to improve resilience by strengthening, adding redundancy to, and relocating vulnerable assets.

"Critical Issues in Transportation 2019: Climate Change Resilience," Vicki Arroyo, *TR News*, Issue 324, November-December 2019.
http://www.trb.org/Main/Blurbs/180592.aspx
From the abstract: This article describes current work on building resilience to climate change impacts. It discusses the activities of the Federal Highway Administration and Federal Transit Administration to improve understanding of climate change impacts; state and local leadership integrating climate resilience in planning; the Transportation Research Board's role in advancing transportation resilience; and future directions for resilience research.

Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance, Susan Asam, Cassandra Bhat, Brenda Dix, Jocelyn Bauer and Deepak Gopalakrishna, Federal Highway Administration, November 2015.
https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf
From the abstract: This guide provides information and resources to help transportation management, operations, and maintenance staff incorporate climate change into their planning and ongoing activities. It is intended for practitioners involved in the day-to-day management, operations and maintenance of surface transportation systems at [s]tate and local agencies. The guide assists [s]tate departments of transportation (DOTs) and other transportation agencies in understanding the risks that climate change poses and actions that can help reduce those risks. Incorporating climate change considerations into how agencies plan and execute their transportation system management and operations (TSMO) and maintenance programs helps the agency

become more resilient to unanticipated shocks to the system. Adjustments to TSMO and maintenance programs—ranging from minor to major changes—can help to minimize the current and future risks to effective TSMO and maintenance.

Measuring and Monitoring Performance

National Resources

Monitoring Indicators and Metrics, Resilience Metrics, National Oceanic and Atmospheric Administration, undated.
https://resiliencemetrics.org/indicators-metrics/monitoring
From the webpage:

> Resilience Metrics aims to answer several critical questions that many planners, resource managers, resilience officers and adaptation practitioners ask:
>
> - What is successful adaptation to climate change?
> - How do we get there?
> - How do we know if we're moving in the right direction?
> - How do we track progress toward resilience goals?
> - How do we measure "success"?
>
> This website offers a user-friendly guide through these challenging questions. You will find tools to help you arrive at answers that fit your local context.

The Monitoring Indicators and Metrics webpage provides information and resources for measuring and tracking the climate resilience of transportation infrastructure, including:

- Funding for monitoring.
- Responsibilities for monitoring.
- Timing, frequency and duration of tracking.
- Appropriate methodologies to collect, analyze and interpret data.
- Resources for monitoring indicators.

State Resources

Florida

Resilience Quick Guide: Incorporating Resilience in the MPO Long Range Transportation Plan, Florida Department of Transportation, January 2020.
https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/planning/policy/resilience/2020-01-29_fdot-resilience-quick-start-guide_final.pdf?sfvrsn=31d65da4_2
Section 2 of this document, which begins on page 6 of the guide, discusses performance measures and provides examples of noteworthy practices used by other transportation agencies. Also provided are links to other organizations' reporting on performance measures and targets.

Iowa

Asset Management, Extreme Weather and Proxy Indicators, Alice Alipour, Omar Smadi, Behrouz Shafei, Nathan Miner, Ning Zhang and Alireza Sassani, Iowa Highway Research Board, Iowa Department of Transportation, February 2021.
https://intrans.iastate.edu/app/uploads/2021/03/asset_management_extreme_weather_and_proxy_indicators_w_cvr.pdf
From the abstract: This pilot project is one among many efforts by the Iowa Department of Transportation (DOT) and the Iowa Highway Research Board (IHRB) to develop and enhance a risk-based transportation asset management plan (TAMP). This project specifically focused on flooding and developed a suite of methodologies and proxy indicators to assess the risk of transportation assets to this hazard.

New York

Climate Resiliency Design Guidelines, New York City Mayor's Office of Resiliency, Version 4.0, September 2020.
https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v4-0.pdf
From the introduction: The primary goal of the [g]uidelines is to incorporate forward-looking climate change data in the design of City capital projects. Codes and standards that regulate the design of facilities already incorporate historic weather data to determine how to design for today's conditions. However, historic data does not accurately represent the projected severity and frequency of future storms, sea level rise, heat waves and precipitation. The climate is already changing and will continue to change in significant ways over the full useful life of facilities designed today, threatening to undermine capital investments and impede critical services if they are not designed for future conditions. … The [g]uidelines complement the use of historic data in existing codes and standards by providing a consistent methodology for engineers, architects, landscape architects and planners to design facilities that are resilient to changing climate conditions.

Related Resources

Hazard-Resilient Infrastructure: Analysis and Design, Edited by Bilal M. Ayyub, American Society of Civil Engineers, 2021.
Citation at https://ascelibrary.org/doi/book/10.1061/9780784415757
From the abstract:

> [This manual of practice (MOP)] provides guidance and an underlying framework for creating consistency across hazards, systems and sectors in the design of new infrastructure systems. The book also discusses enhancing the resilience of existing systems and relates this framework to the economics associated with system life cycle, including organizational and socioeconomic considerations.
>
> This MOP uses probabilistic methods for risk analysis and management of infrastructure projects to address uncertainties within a planning horizon timeframe effectively. This approach includes identifying and analyzing hazards, system failures, associated probabilities and consequences including direct and indirect losses, failure and recovery profiles quantification of resilience, effects on communities, economics of resilience, and technologies for enhancing resilience for new, as well as existing infrastructure. Examples and cases studies are also included.

Chapter 2 provides a methodology for assessing infrastructure resilience as well as a case study.

"Measuring Transportation Infrastructure Resilience: Case Study With Amtrak," Gina Tonn, Jeffrey Czajkowski, Howard Kunreuther, Kara Angotti and Karen Gelman, *Journal of Infrastructure Systems*, Vol. 26, Issue 1, March 2020.
Citation at https://ascelibrary.org/doi/10.1061/%28ASCE%29IS.1943-555X.0000526
From the abstract: This paper describes a case study performed with the U.S. passenger rail service provider Amtrak that developed a metrics framework to measure resilience to climate risk within their Northeast Corridor operations systems and to track changes in resilience over time. Amtrak representatives reviewed metrics and selected those most relevant and also most feasible to measure and implement at Amtrak. Twenty-one metrics, termed resilience activities, focused on technical and organizational (leadership and readiness) resilience; key outcomes to measure following a disruption were identified as cost, safety, customer satisfaction, organizational development and on-time performance. Resilience activities were scored to serve as a baseline for assessing resilience in the future.

"Resilience Metrics and Measurement Methods for Transportation Infrastructure: The State of the Art," Wenjuan Sun, Paolo Bocchini and Brian D. Davison, *Sustainable and Resilient Infrastructure*, Vol. 5, Issue 3, pages 168-199, 2020.
Citation at https://doi.org/10.1080/23789689.2018.1448663
From the abstract: [T]his paper covers different metrics for resilience assessments, with discussions of fundamental challenges due to uncertainties and interdependencies. It points out that validations of resilience assessments are limited due to the general scarcity of data, which may hinder practical applications.

Tools and Technology

State Resources

Multiple States

All Hazards Risk and Resilience: Prioritizing Critical Infrastructures Using the RAMCAP Plus Approach, ASME Innovative Technologies Institute, LLC, 2009.
https://files.asme.org/ASMEITI/RAMCAP/17978.pdf
This excerpt from an e-book published by the developers of RAMCAP Plus describes the benefits of the process:

> For organizations using the RAMCAP Plus process, the direct comparability of consistently quantified risk and resilience levels, potential net benefit and benefit-cost ratios of means to enhance security and resilience can result in rational allocation of resources across sites, facilities assets and lines of business. The benefits of making decisions on this basis are more efficient management of capital and human resources and enhanced reliability in performance of its mission.
>
> ….
>
> A sector adopting the RAMCAP Plus process will be able to identify the components with the greatest need and potential for improvement through the concrete, quantitative RAMCAP Plus assessments. They will have concrete, repeatable descriptions of the current levels of risk and resilience, the potential benefits and benefit-cost ratios of their sector. Adoption also permits direct comparison of the sector's risk and resilience level to other sectors for higher level resource allocation and policy-making.

Related Resource:

Quantitative Method of Risk Assessment for Asset Management Programs, AEM Corporation, 2017.
https://www.taim.psu.edu/assets/docs/quantitative-methods-risk-assessment.pdf
This presentation describes the Risk and Resilience (RnR) approach for highways for asset management, which is derived from the RAMCAP process. References to projects where the approach is used by Colorado DOT (I-70 Risk and Resilience Pilot) and Utah DOT (I-15 and US-40 pilots) are included in the presentation.

Slides 3 through 8 describe the seven-step RnR process followed by examples of RnR for asset management applications in Colorado (slides 9 through 12) and Utah (slides 13 through 14). Findings from the asset management pilots are summarized in slides 16 and 17, and slide 20 provides a complete list of resilience research and pilots.

Maine

Facilitation Tool: Tracking Adaptation Actions, Resilience Metrics, National Oceanic and Atmospheric Administration, 2019.
https://resiliencemetrics.org/sites/default/files/files/Resilience-Metrics-Tool-Tracking-Adaptation-Actions.pdf
This Excel spreadsheet tracking tool "enables an individual/organization to track community adaptation actions being taken over time. The type of actions being tracked [is] based on the Georgetown Climate Center's Adaptation Tool Kit: Sea-Level Rise and Coastal Land Use and the 2015 Successful Adaptation Indicators and Metrics Workshop at the Wells National Estuarine Research Reserve."

Related Resources:

Adaptation Action Tracking Spreadsheet (With Examples from Southern Maine), Wells National Estuarine Reserve, 2019.
https://resiliencemetrics.org/sites/default/files/files/Adaptation%20Action%20Tracking%20Spreadsheet%20(with%20Examples%20from%20southern%20Maine).xlsx
This Excel spreadsheet provides an example of a simple tool used to track adaptation measures for various coastal communities in Maine.

Adaptation Tool Kit: Sea-Level Rise and Coastal Land Use: How Governments Can Use Land-Use Practices to Adapt to Sea-Level Rise, Jessica Grannis, Georgetown Climate Center, October 2011.
Publication available at https://www.georgetownclimate.org/reports/adaptation-tool-kit-sea-level-rise-and-coastal-land-use.html
From the abstract: The Adaptation Tool Kit explores 18 different land-use tools that can be used to preemptively respond to the threats posed by sea-level rise to both public and private coastal development and infrastructure, and strives to assist governments in determining which tools to employ to meet their unique socio-economic and political contexts. To this end, the tool kit also provide policymakers with a framework for decision making. Each tool is analyzed by (1) the type of power exercised to implement it (planning, regulatory, spending, or tax and market-based tools); (2) the policy objective that it facilitates (protection, accommodation, planned retreat, or preservation); and (3) the type of existing or potential land uses that the tool can be used to adapt (critical infrastructure, existing development, developable lands, and non-developable lands). A top level analysis of the trade-offs between tools — the economic, environmental, and social costs and benefits, and the legal and administrative feasibility of implementing each tool — is also provided.

Vermont

Transportation Resilience Planning Tool, Vermont Agency of Transportation (VTrans), 2022.
https://vtrans.vermont.gov/planning/transportation-resilience
From the website: The Vermont Transportation Resilience Planning Tool (TRPT) is a web-based application that identifies bridges, culverts and road embankments that are vulnerable to damage from floods, estimates risk based on the vulnerability and criticality of roadway segments, and identifies potential mitigation measures based on the factors driving the vulnerability. … The TRPT combines river science, hydraulics and transportation planning methods and is applied at a watershed scale. The TRPT was developed and tested in three pilot watersheds and is ready to be applied in these watersheds to inform project scoping, capital programming and hazard mitigation planning for state and local highways. VTrans, in partnership with Regional Planning Commissions, will add watersheds to the TRPT web-application in the future.

Related Resource:

> **User Guide for the Vermont Transportation Resilience Planning Tool (TRPT)**, Vermont Agency of Transportation, January 2019.
> https://vtrans.vermont.gov/sites/aot/files/planning/documents/planning/TRPT%20User%20Guide%201.0.pdf
> This guide for the TRPT tool provides instructions for using the application. Results can be used for "project identification and planning, project prioritization, budgeting, resource and asset management, initial site assessment, starting the scoping and design alternatives analysis, emergency preparedness, hazard mitigation planning, conservation planning, and planning for continuity of business and future housing."

Risk and Vulnerability Assessments

National Resources

Vulnerability Assessment and Adaptation Framework, Third Edition, Gina Filosa, Amy Plovnick, Leslie Stahl, Rawlings Miller and Don Pickrell, Federal Highway Administration, December 2017.
https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf
From the abstract: 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 decision-making. 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 [s]tate departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, maintaining or operating transportation infrastructure.

Related Resource:

Environment/Sustainability/Resilience, Federal Highway Administration
https://www.fhwa.dot.gov/environment/sustainability/resilience/
Access to the Vulnerability Assessment and Adaptation Framework on other resiliency resources are available from this webpage.

State Resources

Multiple States

Resilience, Federal Highway Administration, undated.
https://www.fhwa.dot.gov/environment/sustainability/resilience/index.cfm
From the webpage:

> Extreme weather, sea level change, and changes in environmental conditions threaten the considerable federal investment in transportation infrastructure. FHWA is working with [s]tates and metropolitan areas to increase the health and longevity of the [n]ation's [h]ighways through:
>
> - Assessing vulnerabilities.
> - Considering resilience in the transportation planning process.
> - Incorporating resilience in asset management plans.
> - Addressing resilience in project development and design.
> - Optimizing operations and maintenance practices.

Below are pilot projects from several state DOTs and MPOs:

South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project, Chris Dorney, Michael Flood, Michael Meyer, Gregg Cornetski, Gabe Borroni, and John Lafferty, Broward Metropolitan Planning Organization and Federal Highway Administration, April 2015.
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/south_florida/final_report/south_florida_final.pdf
This pilot project "examined three climate change-related stresses: sea level rise inundation, storm surge flooding, and heavy precipitation induced flooding."

Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure, Capital Area Metropolitan Planning Organization and Federal Highway Administration, January 2015
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/campo/final_report/campo.pdf
The Capital Area Metropolitan Planning Organization (CAMPO) "assess[ed] the potential vulnerability of a limited selection of critical transportation assets in the CAMPO region to the effects of extreme weather and climate, to highlight lessons learned in the process, and to outline potential next steps toward enhancing the resilience of the region's transportation infrastructure. The assets evaluated include roadways, bridges and rail, and the climate-related stressors considered were flooding, drought, extreme heat, wildfire and extreme cold (icing)."

FHWA Climate Resilience Pilot Program: Iowa Department of Transportation, Federal Highway Administration, undated.
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/iowa/fhwahep16047.pdf
From the introduction: To evaluate future flood conditions, Iowa DOT 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 its ability to produce scenarios of future flood conditions. They analyzed the potential impact of the predicted future floods on six bridges to evaluate vulnerability to climate change and extreme weather and inform the development of adaptation options.

FHWA Climate Resilience Pilot Program: Connecticut Department of Transportation, Federal Highway Administration, undated.
https://www.cakex.org/sites/default/files/documents/ctcasestudy.pdf
From the introduction: CTDOT [Connecticut DOT] 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.

Integrating Storm Surge and Sea Level Rise Vulnerability Assessments and Criticality Analyses Into Asset Management at MaineDOT, Maine Department of Transportation and Federal Highway Administration, December 2014.
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maine/final_report/maine.pdf
From the abstract: The project developed and implemented tools to prioritize vulnerable transportation assets in the face of rising sea levels and increasing frequency and intensity of coastal storm surge events. State-owned roads, bridges, and culverts were selected and ranked according to criticality and sensitivity metrics developed in reference to agency maintenance records, flooding histories and the prioritization efforts of agencies in other states.

California

2019 Climate Change Vulnerability Assessments, California Department of Transportation, 2022.
https://dot.ca.gov/programs/transportation-planning/division-of-transportation-planning/air-quality-and-climate-change/2019-climate-change-vulnerability-assessments
This website provides links to summary and technical reports from each of California Department of Transportation's (Caltrans') 12 districts. The reports describe climate change effects in each district and "present detail on the technical processes used to identify these impacts." Cited below are publications produced for Caltrans District 4.

Related Resources:

Caltrans Climate Change Vulnerability Assessments, District 4 Technical Report, California Department of Transportation, January 2018.
https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2019-climate-change-vulnerability-assessments/ada-remediated/d4-technical-report-a11y.pdf
This technical report is "intended to provide a more in-depth discussion of the issues and is intended primarily for District 4 staff. The reader should note that there is some overlap in the material and

information provided in both documents; however, those interested in the complete analysis of potential climate change-related impacts on the State Highway System in District 4 should examine both documents."

This report examines the impact of sea level rise, storm surge, wildfire, temperature and precipitation on transportation infrastructure and discusses metrics to track these variables.

Caltrans Climate Change Vulnerability Assessment Summary Report, District 4, California Department of Transportation, 2018.
https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2019-climate-change-vulnerability-assessments/ada-remediated/d4-summary-report-a11y.pdf
This summary document is a companion to the technical report cited above. The report "outline[s] climate change effects in District 4, the San Francisco Bay Area. … A database containing geospatial data indicating the current and future locations of various natural hazards and their impacts to Caltrans roadways was also developed as part of this project. The maps included in this report and the Technical Report draw upon data contained in this database. Using this data, Caltrans intends to help evaluate the vulnerability of other transportation modes through partnership and data sharing with local and regional agencies. This database is expected to be a valuable resource for ongoing Caltrans resiliency efforts and coordination with stakeholders."

Minnesota

Transportation Resilience, Jeffrey Meeks, Minnesota Department of Transportation, Presentation to Minnesota Transportation Alliance, Nov. 4, 2019.
https://www.transportationalliance.com/sites/ta/files/uploads/Transp%20Alliance_Resilience%20Presentation%2011.04.2019.pdf
This presentation summarizes Minnesota DOT's practices to build climate resilience and its experience with infrastructure vulnerability assessments.

Adaptation Priorities and Costs

National Resources

NCHRP Research Report 938: Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change—Guidebook, Dewberry Engineers Inc., Venner Consulting, Inc., Impact Infrastructure, Inc. and McVoy Associates LLC, 2020.
Publication available at https://www.nap.edu/catalog/25744/incorporating-the-costs-and-benefits-of-adaptation-measures-in-preparation-for-extreme-weather-events-and-climate-change-guidebook
This guidebook was developed "to try to fill the gaps identified by DOTs" and includes "a web-only document NCHRP Web-Only Document 271: Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change, a Power Point presentation that describes the research and the results, a spreadsheet tool that provides an approximate test to see if it would be cost-effective to upgrade assets to the future conditions posed by climate change, and a spreadsheet tool that uses existing conditions without climate change only to calculate the new return period for future conditions with climate change."

Related Resources:

Research in Progress: Design Guide and Standards for Infrastructure Resilience, NCHRP Project 15-80, start date: June 2021; expected completion date: August 2024.
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4971
From the project website: The objectives of this project are to (1) briefly summarize how extreme weather events, long-term climate changes and climate resilience impact transportation project delivery, infrastructure life-cycles and asset management practices; (2) identify current and projected future climate variables to be considered during the design of transportation projects to increase resilience; (3) develop recommendations for updating design processes that include consideration of extreme weather events and increase resilience to climate impacts; and (4) develop a project delivery climate change resilience design guide.

NCHRP Web-Only Document 271: Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change, Dewberry Engineers Inc., Venner Consulting, Inc., Impact Infrastructure, Inc. and McVoy Associates LLC, 2020.
http://www.trb.org/Main/Blurbs/180536.aspx
From the webpage: [This report] is published as a companion document to NCHRP Research Report 938. It includes two frameworks that were developed for the project to allow practitioners to conduct CBAs [cost-benefit analyses] to a level of detail they deem appropriate; a sketch-level analysis can serve as a screening tool to evaluate if adaptation is even appropriate, while a more detailed climate resilience analysis can help to answer the question, "How much can I spend on an adaptation project and have it remain cost-effective?"

Climate Change Adaptation Guide for Transportation Systems Management, Operations and Maintenance, Susan Asam, Cassandra Bhat, Brenda Dix, Jocelyn Bauer and Deepak Gopalakrishna, Federal Highway Administration, November 2015.
https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf
From the abstract: This guide provides information and resources to help transportation management, operations and maintenance staff incorporate climate change into their planning and ongoing activities. It is intended for practitioners involved in the day-to-day management, operations and maintenance of surface transportation systems at [s]tate and local agencies. The guide assists [s]tate departments of transportation (DOTs) and other transportation agencies in understanding the risks that climate change poses and actions that can help reduce those risks. Incorporating climate change considerations into how agencies plan and execute their transportation system management and operations (TSMO) and maintenance programs helps the agency become more resilient to unanticipated shocks to the system. Adjustments to TSMO and maintenance programs — ranging from minor to major changes — can help to minimize the current and future risks to effective TSMO and maintenance.

What Will Adaptation Cost? An Economic Framework for Coastal Community Infrastructure, National Oceanic and Atmospheric Administration Coastal Services Center, June 2013.
https://coast.noaa.gov/data/digitalcoast/pdf/adaptation-report.pdf
From the introduction: A significant impetus for developing this framework was the growing demand from communities for guidance to help protect publicly owned infrastructure, such as roads, schools and sewer systems. However, the holistic approach includes assessing costs and benefits to homes and businesses as well as public assets, and the adaptation strategies discussed in Chapter 2 and Appendix A can be used to protect

both private property and public infrastructure. In fact, some of the adaptation strategies are traditionally employed to protect private, but can be viable options to protect public property as well. You can choose to use this framework to perform a more focused analysis of public infrastructure or to take a broader look at your entire community.

State Resources

California

Caltrans Adaptation Priorities Report — District 4, California Department of Transportation, December 2020. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2020-adaption-priorities-reports/d4-adaptation-priorities-report-2020-v2-a11y.pdf
Note: See page 28 of this Transportation Research Synthesis for the Caltrans Climate Change Vulnerability Assessments report for District 4 citation.

From the introduction: The effort began by determining which assets are most likely to be adversely impacted by climate change in each Caltrans district. That assessment, described in the Caltrans Climate Change Vulnerability Assessment Report for District 4, identified stretches of the [s]tate [h]ighway [s]ystem within the district that are potentially at risk. This Adaptation Priorities Report picks up where the vulnerability assessment left off and considers the implications of those impacts on Caltrans and the traveling public, so that facilities with the greatest potential risk receive the highest priority for adaptation. District 4 anticipates that planning for, and adapting to, climate change will continue to evolve subsequent to this report's release as more data and experience is gained.

Appendix A

Developing Transportation System Climate Resilience Performance Measures: Survey Questions

The following survey was distributed to state departments of transportation expected to have experience with climate resilience performance measures.

Note: Responses to the question below determined how respondents were directed through the survey:

Has your agency developed climate resilience performance measures in one or more of the climate hazard categories listed above?

- No, and we have no plans to do so. (Directed the respondents to the **Wrap-Up** section of the survey.)
- No, but we have performance measures in development or hope to soon. (Directed the respondents to the **Developing Climate Resilience Performance Measures** section of the survey.)
- Yes, we have developed and are using at least one climate resilience performance measure. (Directed the respondents to the **Using Climate Resilience Performance Measures** section of the survey.)

Developing Climate Resilience Performance Measures

Please describe your agency's interest in climate resilience performance measures, including the measures you're developing or contemplating and when you expect to have them in place.

Note: After responding to the question above, the respondents were directed to the **Wrap-Up** section of the survey.

Using Climate Resilience Performance Measures

1. Please identify the climate resilience performance measures your agency has developed in each of the climate hazard categories below.

   Before you begin:

   - If your agency's public website includes a detailed description of these measures, you may provide the appropriate hyperlink(s) in the "Performance measure(s)" or other metric" comment box in lieu of describing each performance measure.
   - If your agency maintains many climate resilience-related measures, please note that MnDOT is most interested in the first three climate hazard categories below (flooding, extreme precipitation events and increasing temperature). *If you have limited time to complete this survey, please focus on these categories.*

Flooding

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Extreme Precipitation Events

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Increasing Temperature

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Heat Wave

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Drought

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Wildfire

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Sea Level Rise

- Performance measure(s) or other metric:

- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

Coastal Storm Surge

- Performance measure(s) or other metric:
- Target value:
- Data sources:
- Methodologies (assumptions, standards and calculations):
- Time interval for evaluation (for example, annually, quarterly or continuously):

2. How does your agency house the data and track the climate resilience performance measures? Select all that apply.

    - In-house database or other tool
    - Commercial database or other tool
    - Suite of databases or other tools (in-house and/or commercial)
    - Internal dashboard
    - Public dashboard
    - Periodic print public report
    - Periodic print internal report
    - Qualitative tracking only
    - Other (Please describe.)

3. Please describe the technology, software or other tools your agency uses to track the climate resilience performance measures. Include in your response:

    - The name of tools and vendors, if applicable.
    - The units or divisions responsible for oversight of the technology, software or other tool.

4. How are the performance measures used within your agency?

5. What challenges have you encountered in developing and tracking climate resilience performance measure?

6. If available, please provide links to a public dashboard, reports and any other documentation related to your agency's climate resilience performance measures. Please send any files not publicly available online to katie.johnson@ctcandassociates.com.

7. Please upload any files not publicly available online or send them to katie.johnson@ctcandassociates.com.

Wrap-Up

Please use this space to provide any comments or additional information about your previous responses.

Appendix B

Developing Transportation System Climate Resilience Performance Measures: Contacts

Below is the contact information for the individuals contributing to this report.

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