Climate Resilience Risk Assessment Tool and Guide: Literature Review, Technology Scan, and Interviews Report

Report No. FHWA-HOP-23-047

November 2023

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

A Federal policy initiative over the past several years has been increasing attention given to climate change, both in the reduction of greenhouse gas (GHG) emissions as well as in providing more resilient communities, infrastructure, and operations. The 2021 Bipartisan Infrastructure Law (Pub. L. No. 117-58) provided formula funding to States and competitive grants to eligible entities, “to increase the resilience of the transportation system” (FHWA 2023a). Prior to this law, many States, metropolitan areas, local governments, and operating agencies had developed plans and adopted strategies to reduce climate change-related risks to transportation systems and to minimize the consequences of such hazards to society in general.

The Federal Highway Administration’s Office of Operations is conducting research to develop a climate resilience risk assessment tool and guide that can support decisions relating to enhancing the resilience of system operations and maintenance activities. The intent is to foster an understanding of the impacts of climate change stressors on existing infrastructure operations, provide a tool to better estimate what these effects might be, and to identify potential adaptation strategies. Transportation agencies can use such a tool to anticipate the risks that extreme weather and climate change pose to their system operations capabilities and to develop a strategy to avoid or mitigate such risks.

This report describes the current state-of-practice with respect to the technologies and practices used by transportation agencies to monitor and predict road weather conditions and to identify potential climate change risks across a range of stressors and asset types. This report summarizes emerging data collection, infrastructure surveillance and monitoring technologies, and similar approaches for monitoring changing environmental and weather conditions. The information in the report is based on a literature review, technology scan, and interviews with transportation agency staff. As such, this report serves as a foundation for the following work on developing the climate resilience risk assessment tool and guide.

Mark Kehrli
Director, Office of Transportation Operations

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA-HOP-23-047</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Climate Resilience Risk Assessment Tool and Guide: Literature Review, Technology Scan, and Interviews Report</td><td colspan="2">5. Report Date
September 2023</td></tr>
<tr><td colspan="2">6. Performing Organization Code:</td></tr>
<tr><td colspan="2">7. Author(s)
Mike Meyer, Principal, MMeyer Consulting
Chris Dorney, Vice President, WSP</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
WSP USA Solutions, Inc.
412 Mount Kemble Ave.
Morristown, NJ 07962</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
693JJ322A000006</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Federal Highway Administration (FHWA)
Office of Operations
1200 New Jersey Ave, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period
Literature and practice review</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HOP</td></tr>
<tr><td colspan="4">15. Supplementary Notes
David Johnson, TOCOR, FHWA, Office of Operations, Road Weather Management Program</td></tr>
<tr><td colspan="4">16. Abstract
The purpose of this report is to identify current and emerging data collection, infrastructure surveillance and monitoring technologies, and similar approaches for monitoring changing environmental and weather conditions. In addition, the report examines the use of risk-based analysis tools to identify road locations potentially vulnerable to such changing conditions. The primary audiences for this report include transportation agency operations and maintenance managers and staff, transportation officials interested in strategies to minimize the impacts of extreme weather events, and those interested in the application of sensing and data collection technologies to manage better transportation system performance.

The report is based on a literature review, technology scan, and on staff interviews from 10 transportation agencies. Most of the technology and practices identified in this report focused on flood monitoring and winter maintenance operations. From a technological perspective, research suggests that many of the challenges of advancing road weather management systems can be overcome with the application of current database management technologies and practices. Piggybacking on current and understood practices in State DOTs seems to be the major focus of many States.

The use of nontraditional technologies as data collection platforms is another notable characteristic of the literature, e.g., use of unmanned aerial vehicles and automated/connected vehicles. There are very few examples of quantitative, risk-based approaches or practices in support of transportation decisionmaking. This is particularly true for traffic and system operations. Most of the literature relating to extreme weather, climate change, and transportation system resiliency, especially the earliest citations, provide general descriptions of potential threats and of possible strategies to minimize the threats. In general, the literature review and interviews suggest that there is still a lack of understanding of risk-based planning and analysis.</td></tr>
<tr><td colspan="2">17. Key Words
Climate adaptation, climate risk, literature review, interviews, climate resiliency, climate, resiliency, road weather, road weather management, road weather management program</td><td colspan="2">18. Distribution Statement
No restrictions.</td></tr>
<tr><td>19. Security Classification
(of this report)
Unclassified</td><td>20. Security Classification
(of this page)
Unclassified</td><td>21. No. of Pages
77</td><td>22. Price
N/A</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AASHTO:	American Association of State Highway and Transportation Officials
ADAP:	Adaptation Decision-Making Assessment Process
ADCIRC:	Advanced Circulation Model
ADOT:	Arizona Department of Transportation
AI:	artificial intelligence
AV:	automated vehicle
AVL:	Automatic Vehicle Location
BC:	British Columbia
Caltrans:	California Department of Transportation
CCTV:	closed-circuit television
CV:	connected vehicle
DelDOT:	Delaware Department of Transportation
DOT:	Department of Transportation
DMS:	Dynamic Message Sign
ESS:	Environmental Sensor Station
FEMA:	Federal Emergency Management Agency
FHWA:	Federal Highway Administration
GIS:	geographic information system
GPS:	Global Positioning System
HEC:	Hydraulic Engineering Circular
IMO:	Integrating Mobile Observations
INDOT:	Indiana Department of Transportation
ITS:	intelligent transportation system
LiDAR:	light detection and ranging
MDSS:	Maintenance Decision Support System®
MnDOT:	Minnesota Department of Transportation
NCAR:	National Center for Atmospheric Research
NCDOT:	North Carolina Department of Transportation
NCHRP:	National Cooperative Highway Research Program
NWS:	National Weather Service

ODOT: Oregon Department of Transportation

PROTECT: Promoting Resilient Operations for Transformative, Efficient and Cost-Savings Transportation

RIP: resilience improvement plan

RWIS: Road weather information system

RWM: road weather management

SANDAG: San Diego Association of Governments

STIC: State Transportation Innovations Council

TAMP: Transportation Asset Management Plan

TB: terrabyte

TEACR: Transportation Engineering Approaches to Climate Resiliency

TMC: Transportation Management Center

TRID: Transportation Research International Documentation

TSM&O: transportation system management and operations

TxDOT: Texas Department of Transportation

UAV: unmanned aerial vehicle

UDOT: Utah Department of Transportation

USACE: United States Army Corps of Engineers

USGS: United States Geological Survey

V2V: vehicle-to-vehicle

V2I: vehicle-to-infrastructure

VAR: value-at-risk

VMS: variable message sign

WRMS: weather-responsive management strategy

INTRODUCTION

The purpose of this Federal Highway Administration (FHWA) Office of Operations, Technical Support Services project is to conduct research and develop a climate resilience risk assessment tool and guide to support transportation infrastructure owners and those responsible for system operations. The intent is to foster an understanding of the effects of climate change stressors on existing infrastructure operations, provide a tool to estimate what these impacts might be, and to identify potential adaptation strategies. Task 2 of this project (Literature Review, Technology Scan, and Interviews) collected information on currently available tools used to identify potential climate change risks across a range of stressors and for a range of asset types. The task was to identify emerging data collection, infrastructure surveillance/monitoring technologies, and similar approaches for monitoring changing environmental and weather conditions. This report summarizes the findings of this information-gathering effort.

The information in this report comes from an online literature review focused on climate risks and their potential effects on transportation infrastructure and operations. The literature review used the Transportation Research International Documentation (TRID) and the ResearchRabbit® search engines to identify relevant reports and studies. In addition, the research team used data from several previously conducted literature reviews that provided a foundation for identifying relevant reports.

The research team also conducted interviews with transportation agencies that have either implemented risk-based approaches in operations practices and/or who have implemented those approaches or are exploring innovative technologies. The project team developed an interview template that included common questions for each group of interviewees and targeted questions for the different groups interviewed (Appendix A). The interview questions emphasized current examples of the state-of-the-practice in climate risk mitigation tools and technologies, potential challenges and gaps, insights on emerging technologies, and opportunities that can enhance risk assessment capabilities. The agencies interviewed included the following departments of transportation (DOTs):

- Arizona Department of Transportation (ADOT)
- California Department of Transportation (Caltrans)
- Delaware Department of Transportation (DelDOT)
- Florida Department of Transportation (FDOT)
- Iowa Department of Transportation (Iowa DOT)
- City of Houston Transportation Department
- Minnesota Department of Transportation (MnDOT)
- North Carolina Department of Transportation (NCDOT)
- Texas Department of Transportation (TxDOT)
- Utah Department of Transportation (UDOT)

Appendix B presents the detailed results of the interviews.

The next section in the report summarizes some of the key literature as it relates to the relationship between transportation system operations, extreme weather, and climate change. The section that follows summarizes key themes found in the reviewed literature. After this, the report provides a summary of the input received through the interviews. The final section of this report synthesizes key findings.

TRANSPORTATION SYSTEM OPERATIONS, EXTREME WEATHER, AND CLIMATE CHANGE IN REVIEWED LITERATURE

Transportation systems operations, a critical part of an agency's ability to provide safety, mobility and accessibility to a State, region, or locale, can be significantly affected by extreme weather and, over time, climate change-related hazards. Extreme weather events might result in road/lane closures, damaged assets, and unsafe road conditions. Longer term climate change risks associated with temperatures, precipitation, winds, and the like could require rethinking design strategies, use of innovative technologies to monitor environmental conditions, and enhancing the capabilities and training of an agency's operations staff.

Uses for Road Weather Information Systems (RWIS)

Road weather information system (RWIS) and road weather management (RWM) systems have many uses. As described by FHWA:

> A Road Weather Information System (RWIS) is comprised of Environmental Sensor Stations (ESS) in the field, a communication system for data transfer, and central systems to collect field data from numerous ESS. These stations measure atmospheric, pavement and/or water level conditions. (FHWA 2022)

Three primary types of road weather information are often collected: atmospheric data, pavement data, and water level data:

- Atmospheric data include air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, cloud cover, tornado or waterspout occurrence, lightning, storm cell location and track, as well as air quality.
- Pavement data include pavement temperature, pavement freezing point, pavement condition (e.g., wet, icy, flooded), pavement chemical concentration, and subsurface conditions (e.g., soil temperature).
- Water level data include stream, river, and lake levels near roads, as well as tide levels (i.e., hurricane storm surge) (FHWA 2022, adapted format).

From an international perspective, according to the World Road Association (the Permanent International Association of Road Congresses, n.d.) RWM may be used to:

- Help prioritize where and when to send maintenance equipment.
- Detect conditions that may be hazardous (such as high winds or flooding)—or that may impact roadway operations. Sensor systems are used to detect other conditions that cause

reduced visibility—such as fog, smoke, blowing dust or sand, and blizzard (whiteout) conditions on roadways.

- Wind-speed sensors on exposed roadways and bridges alert transportation control centers about when they should consider issuing travel advisories for trucks and other large vehicles. When wind speeds are particularly high it may be necessary to impose a (reduced) maximum speed and, in some cases, close the bridge to all traffic.

- Water-level sensors can alert managers when floods are threatening, particularly for flashfloods in normally arid climates or in built up areas when streams and rivers overflow (adapted format).

Although many State/provincial level officials use RWIS and RWM applications, many regional agencies also use the information for their own purposes (SANDAG 2021). This is especially true for developing regional strategies to enhance road safety (Hassan and McClintock 2020).

Research on Climate Change Effects on Roads

A National Cooperative Highway Research Program (NCHRP) research project in 2012–2014 systematically examined the potential impacts of climate change on the Nation’s road network (Meyer et al. 2014). Part of this study looked at the potential effects on Transportation System Management and Operations (TSM&O) and maintenance. For example, with respect to changes in extreme maximum temperatures, the report identified the following possible effects:

- Safety concerns for highway workers limiting construction activities
- Thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs
- Vehicle overheating and increased risk of tire blowouts
- Rising transportation costs (increased need for refrigeration)
- Materials and load restrictions limiting transportation operations
- Closure of roads because of increased wildfires

Other impacts were identified for a range of climate change-related stressors, including:

- Change in the range of maximum and minimum temperatures
- Changes in precipitation and flood levels/frequency
- Changes in storm intensity (including hurricanes)
- Sea level rise

Gopalakrishna et al. (2013) also conducted an early study on the potential effects of climate change and extreme weather on transportation system operations. They determined that systems operations and maintenance adaptations to climate change were one of the important gaps in the available literature and guidance at the time. The study also noted that the scale, frequency, and intensity of extreme weather events will likely change how operations-oriented agencies are organized and function. Table 1 shows the study’s conclusions relating to the potential system operations responses to different climate change effects.

The authors concluded that two of the most important gaps in the literature, which reflected the state-of-practice at the time, was a lack of:

- Approaches for introducing risk assessment in transportation operations planning.
- Approaches for integrating system operations concerns with other adaptation efforts.

The study concluded that the integration of operational considerations such as evacuation procedures, alternate routings, and monitoring should be considered as part of a State's climate change action plans. This recommendation has even greater significance now that States are required to develop resilience improvement plans (RIPs) if they want to lower their match for resilience-related Federal funding (23 U.S.C. 176(e)(1)(B)). This requirement is part of the 2021 Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law, Pub. L. No. 117-58) (FHWA, 2023).

Table 1: Potential Climate Change Impacts to and Potential Responses by System Operations.

Climate Change Effects	System Operations Response
CLIMATE EVENT IMPACTS	
Increased recurring coastal and inland flooding; rising sea levels	• Mandatory diversion to more robust alternative routes • Increased staff and resources to monitor vulnerable routes and provide traveler information
Increase in intensity of tropical cyclones; increased occurrence of wildfires	• Broader preparedness for potential evacuation • Increased Transportation Management Center (TCM) staff and Intelligent Transportation System (ITS) resources to provide traveler information during evacuations • More frequent disaster preparation, operations, and recovery actions
CLIMATE TRENDS IMPACTS	
Increase in energy demand for air conditioning	• Increased need for more resilient TMC communications and backup power to maintain real-time information feeds

Source: Table 1 is adapted from the white paper "Table 2. Climate Change Effects to and Potential Responses by System Operations" published in *Planning for Systems Management & Operations as Part of Climate Change Adaptation and written by Gopalakrishna et al., 2013.*

A subsequent study, the *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance* identified the following possible operations-related consequences from climate change-related disruptions:

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

- Reduced mobility (Asam et al. 2015)

This report used a nonregulatory capability-maturity framework developed by the American Association of State Highway and Transportation Officials (AASHTO) and FHWA for enhancing the TSM&O capabilities within State DOTs. Five capability areas were identified:

- *Systems and technology*: Investments in a suite of technology and management systems to enable more efficiently managed weather events.
- *Performance measurement*: Including measures definition, data acquisition, analysis, and utilization of the measures in decisionmaking.
- *Culture:* Including technical understanding, leadership, commitment, outreach, and program authority.
- *Organization and workforce*: Including organizational structure, staff capacity, development, and retention.
- *Collaboration*: Including internal collaboration and relationships with other public agencies and the private sector (AASHTO n.d.).

The report focused its climate change-related recommendations in six areas:

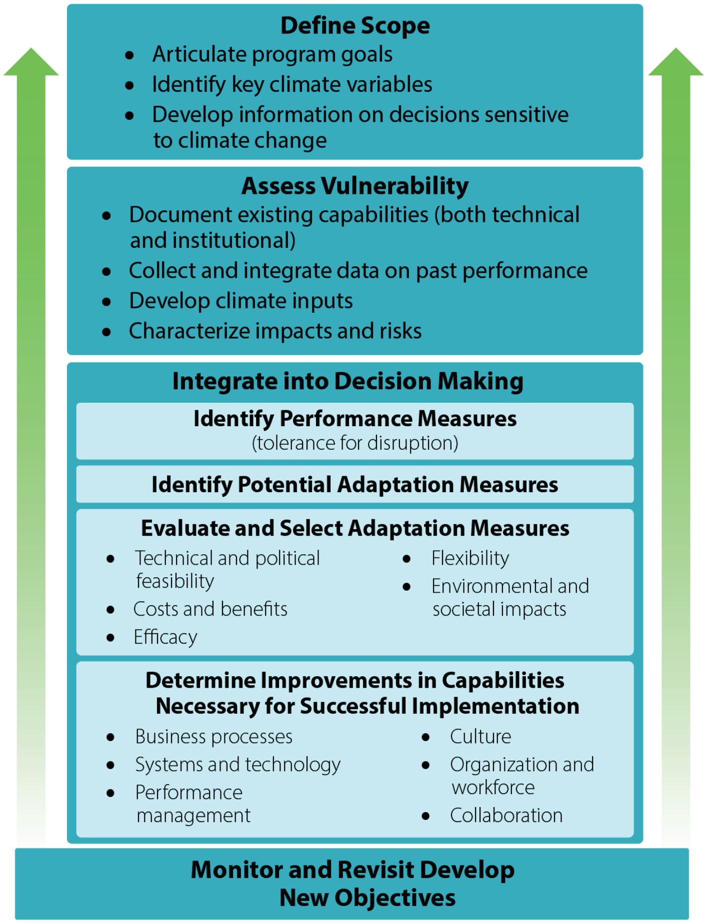
- Business processes
- Financial considerations (e.g., budgeting)
- Risk analyses and dealing with uncertainty
- Planning
- Programming
- Standard operating/implementation procedures

In addition, the report recommended a framework for how TSM&O and maintenance groups could identify and implement appropriate strategies for their unique conditions and locations as shown in Figure 1.

An increasing amount of research has been conducted on the general concept of transportation system resilience and transportation agency decisionmaking. For example, Matherly et al. (2021) developed a “primer” on resilience concepts for transportation executives. Fletcher and Ekern (2021) produced a research road map intended to guide a strategic research effort to add to the knowledge base on resilience and its application in the transportation sector.

NCHRP 970, *Mainstreaming System Resilience Concepts into Transportation Agencies: A Guide* is a targeted study on incorporating resilience concepts into transportation agency decisionmaking (Dorney et al. 2021). This nonregulatory guide provided transportation managers and staff with an agency self-assessment process that can be used to assess the capability/maturity of their agency with respect to resilience. The guide goes on to identify resilience-oriented strategies for areas of deficiency. Two areas of focus are of particular interest to this literature review: emergency response and operations/maintenance. With respect to emergency response, the assessment process included the following questions:

- Does your agency have effective internal and external processes for communicating and sharing emergency response information?
- Does your agency have an "All-Hazards Plan" for responding to emergencies?
- Does your agency periodically field-test critical emergency management technologies, equipment, and systems to ensure performance?
- Does your agency's emergency response/management and security staff interact with other units in your agency (e.g., planning, design, construction, and operations) to provide input on resilience-related aspects of their efforts?
- Does our agency's budget and management support systems consider the staffing surge, equipment, and communications system needs of your emergency response and management strategy (Dorney et al. 2021)?



Source*:* Recreated from Asam et al. 2015.

Figure 1. Chart. Climate Change and Extreme Weather Transportation Systems Management and Operations (TSM&O) and Maintenance Adaptation Framework.

For the operations/maintenance area, the following self-assessment questions are relevant to this literature review:

- Has your agency assessed current operations and maintenance strategies based on the potential vulnerabilities identified earlier?
- Has your agency coordinated the collection of asset condition data as part of its asset management program with ongoing maintenance activities in order to identify the total cost of recurring asset failure?
- Does your agency have contingency plans in the event your traffic management centers (TMCs) are disrupted (e.g., alternative ways of providing traveler information when there is a disruption of the electrical grid)?
- Has your agency implemented a cybersecurity protection plan for critical TMC and operations assets?

Key Themes

This report comprises several sections organized around the following key themes identified during the literature review:

- Technology applications in RWIS, maintenance decision support systems (MDSS), and extreme weather conditions
- Risk assessment approaches and tools, both system- and project-level applications (including benefit/cost methods)
- Hazard-specific technologies, tools, and strategies
- Data

Technology Applications in RWIS, MDSS, and Extreme Weather Conditions

The application of new communication, visual imaging, and sensing technologies predominate in the reviewed literature. Many of the technology-oriented studies and research focused on the use of remote sensing of weather conditions to warn road users of hazardous conditions (Ewan and Al-Kaisy 2017). In general, many studies have examined the potential ***application of intelligent transportation system (ITS) technologies and RWIS*** to provide road owners and users with real-time information on road conditions (Dey and Chowdhury 2015). Tahir et al. (2022) reported on the potential ***use of cellular-based communications on weather and road conditions*** as part of a vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connected vehicle system when delivering road weather and traffic information in real-time environments. They found that the use of such communication technologies for this purpose was feasible and could contribute to an ITS-assisted road weather and traffic platform as reliable information dissemination. A similar study by Stepanova et al. (2020) reported on the ***potential use of vehicular local area networking using V2V and V2I communication tools*** in Finland.

The intent is to deliver near real-time road weather and hazard information directly to the vehicle.

Oscan et al. (2022) conducted research on the ***use of highway cameras*** (both closed-circuit television (CCTV) and mobile snowplow dashcam) as a means of estimating roadway surface conditions. The results were considered promising with an achieved 98.6 percent and 77.3 percent road weather classification accuracy for CCTV and mobile cameras, respectively. The researchers concluded that the proposed use of cameras and a corresponding classification method was suitable for autonomous selection of snowplow routes and verification of extreme road conditions on roadways. Abdelraouf et al. added ***vision imaging technology*** to the use of highway cameras to identify extreme weather-related hazardous road conditions (2022).

Sengupta and Walker (2020) reported on a more ***traditional approach for combining ESS and variable message signs (VMS)*** in British Columbia (BC). The BC Ministry of Transportation and Infrastructure combined ESS and VMS at seven locations on rural highways that experienced extreme winter weather conditions and poor safety performance. Each ESS is connected to two VMS, one in each travel direction. The ESS automatically analyzes weather and road conditions every 15 minutes. After completing the analysis, the ESS's algorithm selects an appropriate sign message and sends it real-time to the road users. The benefits provided by ESS-VMS technology was a 30-percent reduction in severe weather collisions at the study's seven locations and an estimated 4.8 benefit/cost ratio. Although the application was primarily for snow and ice on the roads, the BC Ministry is now looking at using the technology for heavy fog and haze on the roadway.

Prihodko et al. (2021) examined the potential of ***sending information from meteorological monitoring stations to drivers in cars having satellite navigation and onboard systems*** to inform drivers about weather conditions along routes. Knickerbocker and Sassani (2021) examined over 300 dynamic message signs (DMS) used by MnDOT to convey road conditions to road users***. Roadside pavement friction sensors were installed in roadways along with weather messaging*** to detect and report on adverse conditions. These sensors primarily measure skid resistance, which can be affected by environmental conditions (e.g., water on the road), and can give MnDOT staff an indication of what is happening on a particular road location. The DMS used the data to provide cautionary warnings selected from a set of prepared messages. Traffic sensors located before and after the DMS recorded driver speeds and other variables to note changes in driver behavior after passing the displayed warnings. The study found that alerting drivers to icy or snowy roads most often resulted in drivers slowing down and, in some cases, in drivers increasing their following distances after passing the warnings.

Interest in ***using unmanned aerial vehicles (UAV) has grown in recent years***. Several States (e.g., North Carolina, North Dakota, and Utah) have used such technology in a variety of roles such as monitoring the extent of flooding, visualizing road closures for public information purposes, and posting event damage assessment. Szirocza et al. (2022) examined the development and introduction of drone-based mobile automatic weather stations to support improved road weather management. The researchers' review of existing applications indicated that "(1) significant societal-economic value can be generated with the improvement of nowcasting and forecasting systems for road users, (2) technology is ready for the development and introduction of new road weather monitoring and management services, [sic] however, UAV weather tolerance must be improved, and (3) new concepts and software solutions are required for processing the measured data and rapid sharing of nowcasting information" (Szirocza et al. 2022).

El-Rayes and Ignacio (2022) also examined the ***use of mobile ESS that can be deployed on vehicles and the resulting information sent via cellular communications to message boards***. This study examined the effectiveness of combining mobile RWIS, fixed RWIS networks, automatic vehicle location (AVL), and MDSS. A literature review and State DOT official interviews were used to gather the data for this study. One of the key findings of the literature review was the reported cost savings achieved by several State DOTs that deployed mobile RWIS and MDSS during winter maintenance operations. For example, Indiana DOT (INDOT) reported that the use of mobile RWIS and MDSS in 2009 enabled it to achieve annual cost savings of $10,957,672, which includes material savings (salt/brine) of $9,978,536 and labor savings of $979,136. The authors interviewed officials from four State DOTs (Colorado, Indiana, Michigan, and Minnesota). Again, one of the key findings of these interviews were the reported cost savings experienced by several State DOTs. For example, MnDOT reported that the use of mobile RWIS and MDSS in 11 winter events in 2010 enabled it to achieve an average of 53-percent reduction in salt usage for a cost savings of $2,308,866 (FHWA 2019a).

FHWA published a case study of INDOT's use of ***vehicle probe data and developed and applied a suite of Web-enabled tools and performance dashboards using INRIX® probe data*** to improve management of incidents, work zones, snow and ice operations, and signal timing (McNamara et al. 2016; FHWA 2020a). This capability has also supported capital project selection and planning efforts. Interestingly, because of the availability of probe data, INDOT is retiring field detector devices and expects to remove approximately 50 percent of its roadside equipment sites.

The technology of road user weather information has also changed over time, with ***new advances in sensors and weather data collection married with new communications and information exchange technologies***. An example of this is the FHWA Office of Transportation Operations' 2001 prototype initiative to develop a winter road MDSS (NCAR 2023). This initiative was expanded significantly by a State DOT pooled-funded study led by the South Dakota DOT and included 15 other State DOTs. Those State DOTs have been developing and testing MDSS as an operational tool in the States involved in the study (FHWA 2015a). The intent of MDSS is to support effective winter maintenance decisions (treatment types, timing, rates, and locations) through the use of weather forecasts as inputs to a pavement heat balance model that predicts the road surface and subsurface temperatures and the snow depth at each forecast lead-time. Treatment plans are then developed for each site with a graphical user interface display designed for easy interpretation by road maintenance managers. The overall objectives of the MDSS capability are to perform the following actions:

- Capitalize on existing road and weather data sources.
- Augment data sources where they are weak or where improved accuracy could significantly improve the decisionmaking task.

- Fuse data to make an open, integrated, and understandable presentation of current environmental and road conditions.
- Process data to generate diagnostic and prognostic maps of road conditions along road corridors, with emphasis on the 1- to 48-hour horizon (historical information from the previous 48 hours will also be available).
- Provide a display capability on the state of the atmosphere and roadway.
- Provide a decision support tool, which provides recommendations on road maintenance courses of action.
- Provide all of the above on a single platform, with simple and intuitive operating requirements. Also, provide a readily comprehensible display of results and recommended courses of action together with anticipated consequences of action or inaction (NCAR 2023, adapted to a bullet list) (FHWA 2015a).

Oregon DOT's (ODOT) use of a ***combination of RWIS and communications technologies*** is an example of how typical configurations are set up (Oregon DOT 2022). The project included the installation of RWIS, speed sensors, travel time readers, and changeable message signs at seven locations in the U.S. Hwy. 97 corridor. The project team expected that message signs would also provide the ODOT's TripCheck system with additional traveler information. TripCheck is an ODOT website that provides roadside camera images and detailed information about Oregon road traffic congestion, incidents, weather conditions, services, and commercial vehicle volumes. The cost of the U.S. Hwy 97 installation was just over $3.1 million.

The States in the following list have strategies similar to Oregon DOT's:

- Alaska DOT and Public Facilities (AKDOT&PF), https://roadweather.alaska.gov/gis
- Minnesota DOT, https://www.dot.mn.gov/maintenance/rwis.html
- Ohio DOT, https://www.transportation.ohio.gov/programs/traffic-management/resources/04-weather-management
- Vermont Agency of Transportation, https://vtrans.vermont.gov/operations/rwis
- Washington State DOT, https://tsmowa.org/category/intelligent-transportation-systems/road-weather-information-systems

Pisano (2019) reported on two FHWA initiatives which are part of its Weather-Savvy Roads program that promotes innovative approaches that address weather effects on the road systems—Pathfinder and Integrating Mobile Observations (IMO***). Pathfinder focuses on establishing the institutional relationships*** necessary for providing effective impact messaging to road users and IMO ***promotes enhanced data collection from agency fleet vehicles to improve road users' awareness of road conditions***.

Pathfinder is a collaborative effort among a State DOT, the National Weather Service (NWS), and contracted weather service providers. The suggested approach is an eight-step process to build on existing practices that share forecasts and road conditions among the project partners and then translate that information into consistent impact messages for the traveling public. This effort involves, "assessing the types of information to share and how to share it before, during, and after high-impact weather events. The goal is to provide the public with consistent and actionable messages on potential impacts on the transportation network" (Pisano 2019). The paper notes Pathfinder benefits as enhanced decisionmaking, better-informed travelers, the potential for reduced vehicle miles traveled, improved maintenance operations with less motorist impedance, and increased overall safety. The costs of developing Pathfinder are primarily associated with the time agency staff and the weather service provider required to conduct collaborative activities.

IMO focuses on the collection of weather, road, and vehicle data from agency fleet vehicles to improve situational awareness of road conditions. The technology needed to collect data is already available on most State DOT vehicle maintenance fleets, including AVL and real-time communications. As reported in the Pisano paper, IMO enhancements involve ancillary sensors that collect data on weather and road conditions such as air pressure, atmospheric and pavement temperatures, pavement condition status, spreader rate and materials, windshield wiper status and rate, and relative humidity. IMO benefits noted by State DOTs included cost savings from the reduced salt and sand usage, increased accuracy of informed decisions based on real-time information about material applications, potential for increased reporting efficiency, reduced time spent relaying information, improved situational awareness, reduced resources needed to respond to emergencies, and, over time, reduced equipment usage and lower legal costs due to fewer tort claims.

Risk Assessment Approaches and Tools

Several studies over the past 5 years have focused on incorporating risk concepts into agency decisionmaking, with asset management having the most applications. For example, nonregulatory NCHRP Report 985, *Integrating Effective Transportation Performance, Risk, and Asset Management Practices*, defined risk management as, "Identifying and responding to the inherent uncertainties of managing a complex organization through a process of analytical and management activities related to finances, asset condition, and climate change" (Jacobs Engineering 2022).

As noted in the NCHRP report, the adoption of risk-based planning and decisionmaking has been "significantly more uneven" in nonasset management areas as compared to agency adoption of asset management and performance measures. The report did not include detailed quantitative risk parameters in the calculation process. However, the report did cover the expected costs and benefits associated with resilience/adaptation strategies. For example, possible costs for such strategies/projects/designs included the following (limited) broad categories:

- Monetary cost for implementing the action.
- Environmental and social costs.

Possible benefits included factors that were primarily defined as loss avoided due to the implementation of the action, including reductions in the following areas:

- Physical damage
- Response and recovery costs
- Revenue loss (e.g., toll revenues)
- Economic losses
- Transportation service losses (such as detour times, travel time delays, vehicle wear and tear, crashes)

Note that this categorization of benefits and costs reflect the typology that is most often used in benefit/cost analysis, that is, benefits are the reduction in costs incurred by the owner of the facility (e.g., a State DOT), users of the facility (e.g., automobiles and trucks), and by society at large (e.g., economic losses and loss of community connectivity).

Systems-Level Assessments

Risk assessment approaches and tools that can be used in support of transportation decisionmaking are relatively new concepts. With respect to extreme weather and climate change, much of the early work in developing approaches and tools were not risk-based in the sense of providing a quantitative indication of what the risks might be to different groups potentially affected by transportation system disruptions. Many of the systems-level approaches relied on indicators, both quantitative and qualitative, to provide some sense of where assets vulnerable to extreme weather events are located and the degree to which they might be vulnerable to different stressors caused by expected hazards and climate threats. These approaches were largely based on a Vulnerability Assessment and Adaptation Framework, developed and modified by FHWA based on the results of numerous pilot studies conducted around the country (Filosa et al. 2017).

A study in Canada examined future climate risks in the context of the then current condition of Canada's infrastructure and the effects of climate change (Felio 2015). The study presented a high-level overview of some of the ***tools available to decisionmakers and infrastructure practitioners to consider climate change impacts, from planning to operations and maintenance***. It also focused on processes and methodologies that have been used by public agencies and municipalities in Canada to identify and quantify risks, as well as to develop climate change adaptation solutions.

Colorado DOT (CDOT) conducted one of the first system-level assessments of a range of hazards along the I–70 corridor (Colorado DOT 2017). Resilience scores were calculated for different segments of the interstate highway relating to the expectation of disruption from a natural hazard and the costs to CDOT and to road users from the perspective of increased travel time and increased crashes from using detours. The study also recommended 15 actions for CDOT to improve integration of risk and resiliency into agency operations.

In order to understand the steps that are necessary for quantifying risk (at least in terms of physical infrastructure), examining a study in more detail is useful. Perhaps one of the more robust examples of climate change risk-based assessment was undertaken for MnDOT and examined flood vulnerability (MnDOT 2022). Agency officials were interested in developing a method to understand the flood risk to important agency assets; in particular, bridges, bridge culverts, and pipes. MnDOT management expected the increased understanding of such risks to lead to prioritizing assets for facility-level adaptation assessments, feed into the development of the transportation asset management plan (TAMP), better inform emergency response planning, and identify potential enhancements to operations and maintenance activities. MnDOT prepared flood exposure projections based on climate scenarios up to the year 2100. They also quantified risk estimates by calculating the lifecycle costs of the "do nothing" alternative through the year 2100.

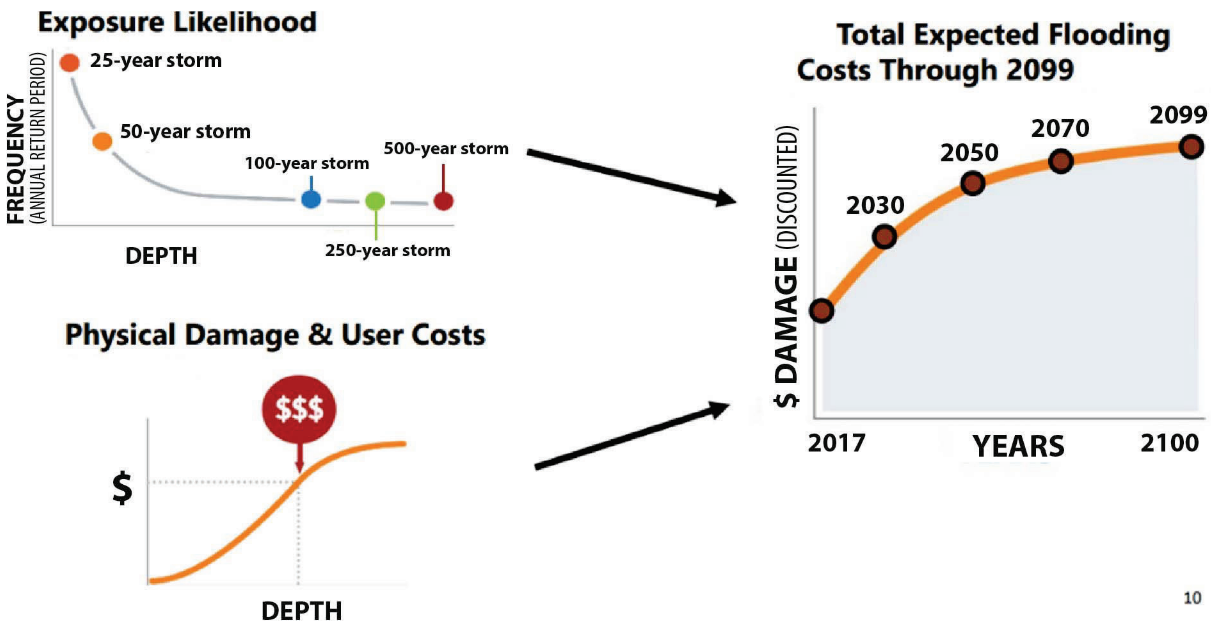
Another ongoing study for the Massachusetts DOT is similar in concept to the MnDOT study. The MassDOT planning-level study of transportation assets examines assets at risk to flooding over the coming century. The focus is on the State's National Highway System roads, bridges, and large culverts, MassDOT- and Massachusetts Bay Transportation Authority-owned rail infrastructure, MassDOT facilities, and many public-use airports. From a risk perspective, the study assesses damage and repair costs, time estimates for repairs, and monetary consequences for riders due to loss of service. A similar study was undertaken for Pinellas County, FL (Tampa) that focused on coastal hazards (tidal flooding and storm surge with sea level rise factored in) (Pinellas County 2020).

In both studies, risk was measured as the cost of replacement and damage repair as well as costs to system users from climate stressors if no adaptation actions were taken. Both studies also used information from the following items to estimate costs:

- A roadway damage model considering:
  - Pavement delamination
  - Embankment erosion
- A culvert damage model considering:
  - Loss via embankment erosion
  - Outfall erosion
- A bridge damage model considering:
  - Pavement delamination
  - Deck damage/displacement
  - Pier, abutment, and contraction scour

Estimated costs to the traveling public for detouring around a flood-impacted asset considered traffic volumes; network redundancy; estimated outage durations; and time, fuel, and operating costs. This estimation was based on a geographic information system (GIS) custom-designed detour routing algorithm.

Figure 2 shows the logic in estimating risk over the climate scenario timeframe. In essence, the estimates are based on depth/velocity-damage relationships that indicate expected costs associated with various magnitude floods. The expected costs, based on an estimated frequency of occurrence, are discounted over the life of the asset, resulting in a quantified risk estimate.



Source: Minnesota Department of Transportation 2022

Figure 2: Quantifying Flood Risk.

The methodology for estimating flood risks consisted of two phases:

- Phase 1, the flood exposure analysis, included preparing hydraulic model inputs, running the hydraulic model, and incorporating hydraulic model outputs in GIS.
- Phase 2, risk analysis, included preparing the risk model asset data inputs, preparing the risk model user data inputs, and running the risk models.

Risk models tally the expected cost by damage mechanism by year and simulation for each climate scenario and asset. These damage cost events are then discounted and summed across the lifecycle of the asset.

The MnDOT, MassDOT, and Pinellas County studies relied on a technique for considering risk tolerance when interpreting systems-level risk assessment results. The technique involves splitting the estimated costs (risk) into future time horizons, and then each DOT determines the acceptable level of costs it might incur over a given period. The DOT identifies any asset expense exceeding this risk-tolerance threshold to be an exposed asset and a candidate for facility-level assessment to evaluate mitigation measures. This relatively simple technique provides the benefits of both explicitly defining a risk threshold and helping to determine the timing (and, therefore, priority) of when to take action.

In summary, two key observations of the use of systems-level risk assessment tools in transportation decisionmaking are important for this project. First, ***no examples were found for which such tools were used for traffic operations, extreme weather, or climate change*** (although quite a few risk-based approaches were reported for traffic safety decisionmaking). Second, even for climate change-related risk assessments outside of traffic operations, the literature review uncovered ***very few applications of quantitative risk measures*** as were found in other fields such as public health, national defense (Melnick and Everitt 2008), and in transportation for such topics as the transportation of hazardous materials and transportation security (Nicolet-Monnier and Gheorghe 1996).

Project-Level Assessments and Benefit/Cost Methods

Risk assessment and benefit/cost approaches have been developed for risk-based, project-level assessments, although they are not widely used. A detailed project-level approach to risk assessment has evolved over the past 10 years. For example, Armstrong et al. (2014) reported an approach for assessing quantitative risks for individual facilities and assets based on the following information:

- Outcomes of a ***series of engineering assessments*** to identify implications of incorporating climate variability in projects already completed/underway
- Development of ***policies for including risk as part of decisionmaking in planning and engineering***
- Development of ***methods to prioritize improvements to reduce/eliminate risks*** to the existing network
- Development of methods to incorporate climate change and/or extreme weather into decisionmaking for planning and engineering projects

The framework developed in this study includes a consideration of the design life of transportation facilities, replacement cost values, and an assignment of loss scores for damage/loss value—all of which were utilized in this benefit/cost framework.

The Adaptation Decision-Making Assessment Process (ADAP), developed and evolved as part of FHWA's climate change efforts, is an advanced approach for considering climate change-related risk during project development (FHWA 2019b). ADAP is intended as, "a risk-based tool to aid decisionmakers in determining which project alternative makes the most sense in terms of lifecycle cost, resilience, regulatory and political settings, etc." (FHWA 2019b). ADAP can be used for these applications:

- To assess existing assets for their sensitivity to extreme weather and projected climate changes.
- To design new infrastructure projects.

For new projects, ADAP can be applied during the planning stage of project development to provide the maximum opportunity to explore project alternatives. Figure 3 shows the 11-step process as a decision tree. Note the use of scenarios to show the potential range of climate change effects on a facility.

The ADAP process was used in several proof-of-concept studies for FHWA and State DOTs. Examples include the *FHWA Transportation Engineering Approaches to Climate Resiliency* (TEACR) study for different types of assets (FHWA 2015b), as well as in pilot studies for the

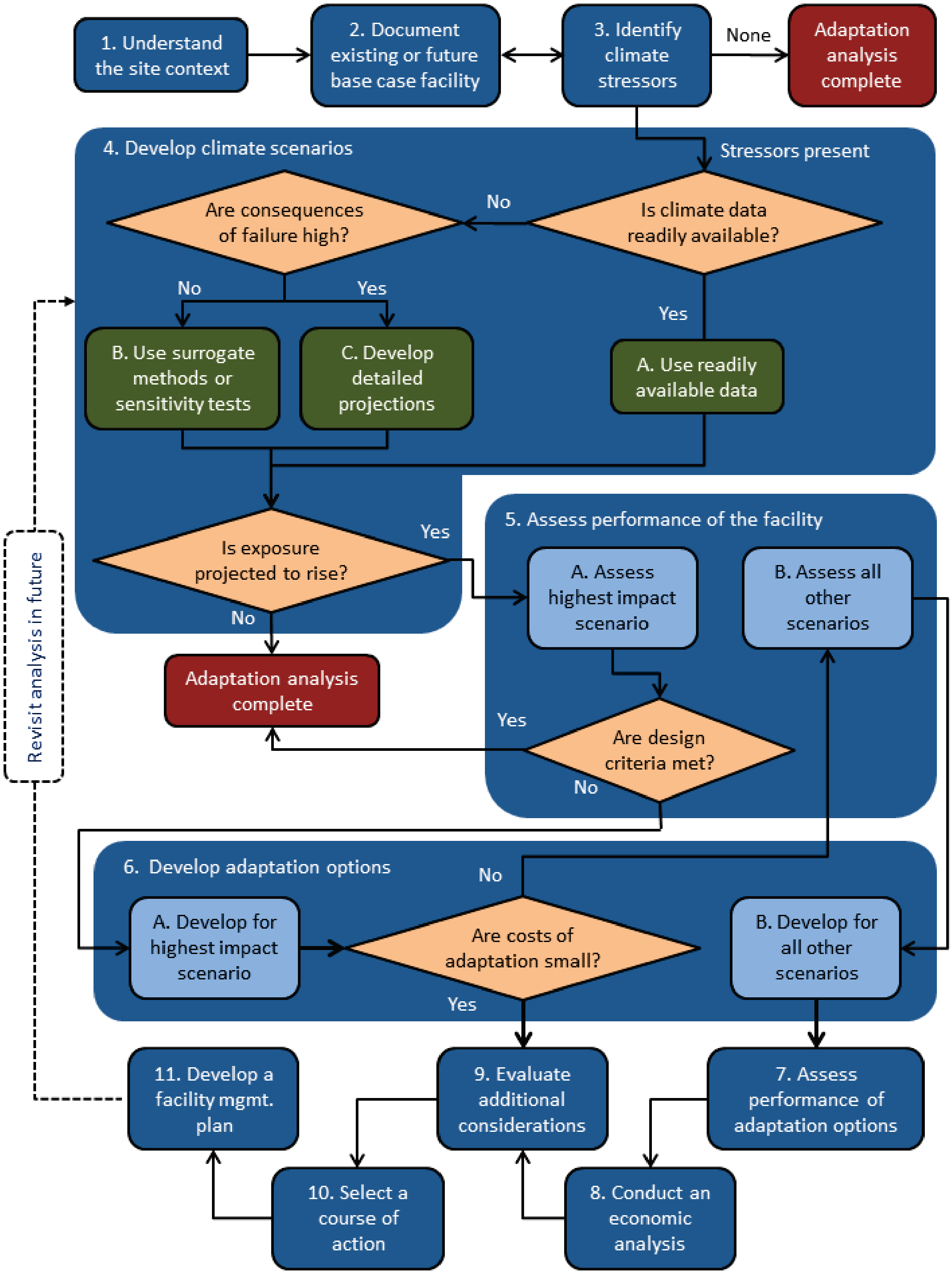
California Department of Transportation (Caltrans), the Minnesota DOT (MnDOT), Pinellas County (FL), and others. A summary of lessons learned in the TEACR study, in addition to specific recommendations for each type of asset-stressor combination, came to the following conclusions:

- Assets' performance should be tested against several future scenarios to understand the range of possible impacts. FHWA's Highway Engineering Circular (HEC)-25 Volume 3 (FHWA 2020b) and HEC-17 (FHWA 2016a) provide detailed guidance on how to select scenarios, make decisions about models and timeframes, and adjust regional global projections so that they reflect local conditions.

- The selection of adaptation measure(s) should include a consideration of the surrounding environment, the future of the transportation system of which the asset is a part, and socioeconomic considerations. Budgetary considerations may also come into play.

- Adaptation solutions should, whenever possible, be flexible. The transportation system, surrounding communities, and projections of future conditions may change over time. Adaptive management approaches that recognize this, in general, provide a hedge against uncertainty in future conditions. An example of an adaptive management approach would be a road designed with a stronger foundation than is needed for today's conditions so that it is capable of being raised at less expense in the future should a more rapid rise in sea levels occur.

- ***Benefit/cost methodologies have been developed for and applied in project-level risk assessments.*** One of the steps in ADAP is to conduct benefit/cost assessments of the adaptation options being considered for a project. FHWA conducted an ADAP assessment focused on economic analysis as part of the TEACR study (FHWA 2016b). Other risk-based, facility-level benefit/cost analyses have been conducted using the ADAP framework throughout the country spanning a wide range of asset-hazard combinations (e.g., coastal flooding, riverine flooding, landslides, wildfire, etc.), many of which considered extreme weather in the context of future climate changes. Using the lessons learned from the aforementioned TEACR case study, a Monte Carlo-based model was developed for conducting economic analyses for facility-level risk assessments that can be readily modified to cover different asset-hazard combinations. The model considers future climate change and the impacts this might have on extreme weather probabilities and risk.



Source: FHWA 2019b.

Figure 3: FHWA's Adaptation Decisionmaking Assessment Process (ADAP).

- Dewberry Engineering et al. (2020) conducted a recent NCHRP study that provided a resource for transportation practitioners to more readily consider benefit/cost analysis as a tool in investment decisionmaking when considering different climate and extreme weather adaptation alternatives. The proposed approach used extreme event return periods as a means of introducing uncertainty in projected future disruptions (FHWA 2017).

Benefit/cost assessments have been developed focusing on the different groups that would benefit from the use of RWIS technologies. Research has been conducted on how benefit/cost assessments can be undertaken to determine the benefits in implementing RWIS technologies, usually defined by the groups that would benefit (Pilli-Sihvola et al. 2015). One of the first efforts was a 1988 Strategic Highway Research Program project that looked at the potential effectiveness of RWIS technologies for improving and reducing costs of highway snow and ice control. At the time, the technologies investigated included pavement and meteorological sensors, pavement condition forecasts, roadway thermography, and electronic communications required for effective dissemination of the information (Bosselly 1992). A statistical model was used for the benefit/cost assessment that included dimensional matrices as the basis for computing costs. Benefits were the reductions in snow and ice control costs resulting from the use of the weather information technologies. The study showed that detailed forecasts of road conditions provide the greatest benefit/cost ratio; however, the combination of forecasts, sensors, and road thermography synergistically provided improved level of service for snow and ice control, a significant reduction in decision errors, as well as a benefit/cost ratio much greater than 1.

The general approach for the assessment is to adopt a lifecycle benefit/cost model for when the benefits and costs would occur over the RWIS lifespan. McKeever et al. was one of the first studies applying such an approach to RWIS technologies (1998). The tool developed in that study provided highway agency decisionmakers with, "a methodology through which different RWIS implementation alternatives can be evaluated from economic, qualitative, and environmental perspectives." Veneziano et al. applied the lifecycle approach specifically to determine the desirability of RWIS technologies for winter maintenance programs (2014). Case studies of the tool application illustrated the level of benefit that could be achieved. In one statewide application in Iowa, the study found that RWIS produced an agency-specific benefit/cost ratio of 3.8 and a total (i.e., societal) ratio of 45.4. A second case study of one subdistrict in Indiana found that a benefit/cost ratio for the agency would be 1.5 while the total ratio, which included user costs, would be 3.0.

Hazard-Specific Technologies, Tools, and Strategies

Most tool advancement is found in integrated flood modeling: The literature review found numerous articles and reports describing various approaches to monitor flood levels and then passing this information on to the users of impacted roads (Transportation Research Board (TRB) 2019). Other hazard types were not as well represented in the literature. Park et al. (2021) developed a synthesis of the scope and impact of practices that have been applied to integrated flood prediction and response systems for transportation systems. Table 2 shows a sample of States that responded to a survey requesting information on how they monitor, predict, and respond to flood events. As indicated in the table, there is a range of methods, data sources, and uses of such data among the States.

The synthesis also reported some interesting responses from the State DOTs regarding several characteristics of the use of integrated flood monitoring and warning systems. Given that the information reported in the synthesis is useful for other types of innovative extreme weather monitoring and response systems, several of the tables in the synthesis are presented below.

Table 2: Sample of State Approaches to Integrated Flood Monitoring and Modeling.

State	Approach
Arizona DOT (ADOT) *(Note: More information provided in interview reported below)*	The Arizona Flood Warning System is an interactive map for users to determine precipitation data and water level in tabular and graphical format:
Caltrans	• The Commercial Wholesale Web Portal by Caltrans is a system that provides high-resolution weather, visibility, and environmental data to in-field ITS devices throughout the 12 districts. • Review of State of Practice—Evaluating the Performance of Transportation Infrastructures during Extreme Weather Events. Ibrahim-Watkins (2018) states that the methods used to predict large inundation events are effective in reducing repair costs and increasing safe evacuation, but more diverse methods are needed. • The preliminary investigation in Flood Warning Alert Systems found that many States, like California, need a flood alert system that allows them to proactively monitor, assess, and respond to flood disasters in real-time (Lissade 2012).
Delaware DOT (DelDOT) (Note: More information provided in interview reported below)	• Delaware has a statewide flood monitoring system of 10 hydrology gauges with real-time water levels. • The Delaware Coastal Monitoring System is an alert system used to provide information to planners, emergency managers, and others about future coastal events. • DelDOT Gateway is DelDOT's interactive map with 28 layers including prediction of sea level rise.
Idaho DOT	The success of Idaho DOT's successful flood monitoring systems is attributed to real-time bridge flood monitoring software and the Idaho Transportation Board Scour Committee.

State	Approach
Iowa DOT (Note: More information provided in interview reported below)	• Iowa DOT noted that Real-time bridge flood monitoring software has allowed it to conduct successful flood prediction modeling. The Iowa Flood Center's flood prediction and Iowa Flood Information System have also contributed to Iowa DOT's success. • The hydrological model CUENCAS had been used to predict flooding in small tributaries in the Squaw Creek basin in Iowa. The goal of this project is to eventually develop a reliable real-time flood forecasting system to produce actionable results for those maintaining roadways during extreme flood events. • WeatherView is an interactive map by Iowa DOT that reports live weather conditions with data from Automated Weather Observing Systems (AWOS) and RWIS. • The Iowa Flood Information System (IFIS) allows web-based access to flood-related information, visualization, and application. The website provides easy access to links of flood alerts, stream conditions, river communities, and inundation maps. • As a part of its weather-responsive management strategies (WRMS), Iowa DOT redesigned its 511 traveler information map, where it improved its traditional closure icons and added painted lines to show the extent of closures, construction, and other applicable events.
Louisiana DOT and Public Facilities	United States Geological Survey (USGS) HydroWatch is an interactive map of United States Army Corps of Engineers (USACE) river gauges, USGS HydroWatch devices, movable bridges, and water body locations.
New Jersey DOT	UAV initiatives include structural inspections, emergency response assessments, traffic congestion management, aerial 3D corridor mapping, and watershed surveys.
New York State DOT	The New York State Department of Transportation (NYSDOT) uses NWS flood warnings and Real-time bridge flood monitoring software. NYSDOT also uses the USGS' StreamStats program for flood prediction and is working on further developing its StreamStats usage.
Oklahoma DOT	Developed a decision support system to predict threats on roadways and remotely turn on advanced warning lighting or gates to close roads during dangerous flood emergencies.

State	Approach
Texas DOT (Note: More information provided in interview reported below)	• Tested NWS's National Water Model through the installation of 20 radar streamflow gauges on bridges on or near Interstate Highway 10, which can help forecast flooding in real-time using water velocity and water level to find stream discharge in the USACE's Hydraulic Engineering Center River Analysis System HEC-RAS two-dimensional model. • Houston TranStar—in coordination with the Harris County Flood Control District's Flood Warning System—has created a real-time flood warning system that alerts travelers in high-risk areas during a rain event (Houston TranStar 2023).
Utah DOT (Note: More information provided in interview reported below)	• Road weather interactive map includes road condition forecasts, city forecasts, and current conditions. • Citizen Reporting is a program through UDOT in which trained roadway users can report on current roadway conditions to enhance coverage of weather on roads.
Washington State DOT	Uses WatchList for monitoring critical locations during flood events.

Source: Park et al. 2021.

Table 3 shows the different practices for flood monitoring. Table 4 shows the types of tools and approaches used in data collection. Table 5 shows the different models used for flood prediction. Table 6 and table 7 show the observed benefits of using flood monitoring techniques and of using integrated flood monitoring and warning systems, respectively. Table 8 shows the indicated issues State DOTs face in implementing flood prediction models and approaches. Table 9 indicates the challenges faced in flood event response.

Park et al.'s (2021) synthesis identified the following knowledge gaps and future research needs:

- The need for advancements in data collection (e.g., bridge scour) was a key issue for most of the States interviewed. There is a need to understand the required resolution of data needed (e.g., issues with the stream network without the monitoring gauges or low-frequency monitoring) and data continuity (e.g., for identifying hydrodynamics).

- There is a lack of current data on flooding hazards, which includes costs and social impacts.

- Although hydrology and hydraulic modeling challenges differ depending on land cover and physiographic region, there is a need to improve real-time flood model predictions, especially for backwater flow conditions and other hydrologically complex areas (i.e., snowmelt flooding or king tides).

Table 3: Different Practices and Approaches to Flood Monitoring.

Practices and Approaches	Number of States Indicating (N=43)
Use of local weather information	24 (56%)
Other (e.g., field monitoring, state river forecasts)	12 (28%)
Dynamic flood inundation map	8 (19%)
National Weather Service	8 (19%)
National Water Model	6 (14%)
Real-time bridge flood monitoring software	4 (9%)
State model	3 (7%)
United States Geological Survey gauges	3 (7%)

Source: Park et al. 2021.

Table 4: Reported Instruments and Tools Used in Data Collection.

Practices and Approaches	Number of States Indicating (N=43)
Stream gauges (Federal)	41 (95%)
Rain gauges (federal)	25 (58%)
Stream gauges (non-federal)	21 (49%)
Geographic information system (GIS)	17 (40%)
Radar	16 (37%)
Other (e.g., staff field investigation)	14 (33%)
Rain gauges (non-federal)	14 (33%)
Video	11 (26%)
Remote-sensed data	11 (26%)
Unmanned aerial vehicle	8 (19%)

Source: Park et al. 2021.

Table 5: Flood Prediction Models.

Practices and Approaches	Number of States Indicating (N=35)
Hydrologic/Hydraulic Models	18 (57%)
Other (e.g., maintenance staff)	9 (26%)
Threshold model	4 (11%)
National Oceanic and Atmospheric Administration	2 (6%)
Real-time bridge flood monitoring software	2 (6%)

Source: Park et al. 2021.

Table 6: Observed Benefits of Using Flood Monitoring Approaches.

Observed Benefit	Number of States Indicating (N=30)
Improved emergency response	23 (77%)
Improved understanding of maintenance needs	23 (77%)
Improved emergency planning	20 (67%)
Improved understanding of system performance	17 (57%)
Improved emergency evacuation	12 (40%)
Other (e.g., better communication)	7 (23%)

Source: Park et al. 2021.

Table 7: Observed Benefits of Using Integrated Flood Monitoring and Warning Systems.

Observed Benefit	Number of States Indicating (N=25)
Safety benefits such as reduction in crashes	21 (84%)
Interagency communication	17 (68%)
Improved relationships with State DOT offices	17 (68%)
Positive public feedback/trust (enhanced reliability in State DOT warnings)	12 (48%)
Reduction in economic loss (e.g., reduced infrastructure repair)	10 (40%)
Better understanding of the performance of flood conveyance systems	9 (36%)
Enhanced common database	8 (32%)

Source: Park et al. 2021.

- Research is needed to address difficulties and challenges in facilitating database sharing and integration (e.g., incorporating disparate data types). There is also a need to share and incorporate heterogeneous data between agencies and States, as well as stakeholders. Spatial-temporal databases could better facilitate data sharing, modeling, and analysis of the flooding risks and impacts on the transportation infrastructure.

- Methods are needed for further integration of developed flood monitoring software into State DOTs' real-time monitoring systems while overcoming various issues associated with data format, type, resolution, and quality. Furthermore, an investigation is needed to determine an optimal warning-level setting for a range of scenarios to minimize false alarms, because the degree of false alarms varies according to local hydrology and hydraulics.

Table 8: Reported Issues in Implementing Flood Prediction Models.

Observed Benefit	Number of States Indicating (N=46)
State resources (e.g., staff, funding, turnover)	36 (78%)
Technical expertise	18 (39%)
Data coverage	15 (33%)
Local resources (e.g., staff, budget)	14 (30%)
Data format consistency	12 (26%)
Other (e.g., proprietary data, underlying science unclear)	11 (24%)
Date accuracy	10 (22%)
Data accessibility	7 (15%)
Data completeness	6 (13%)
Difficulty in integrating Federal resources	6 (13%)
Data timeliness	4 (9%)

Source: Park et al. 2021.

Table 9: Reported Challenges in Flood Event Response

Observed Benefit	Number of States Indicating (N=46)
Lack of resources (e.g., staff, funding, technical expertise)	24 (52%)
Other (e.g., interagency coordination)	16 (33%)
Lack of commonality of databases	13 (28%)
Lack of concern or understanding of flood risk	8 (17%)
Lack of prioritizing from state leadership	6 (13%)
Lack of stakeholder interest	4 (5%)
Data security	2 (4%)

Source: Park et al. 2021.

- Urbanization and land development result in more frequently observed intense runoff events; the highly dynamic nature of these areas makes flood prediction particularly challenging. To better mitigate the impacts of intense runoff events, research is needed to better predict the downstream impacts of urbanization and land development.

- A gap was identified in the single-asset, single-issue focus of the most common transportation decisionmaking systems. It is considered to be a gap because flood events are typically attributable to various incidents that can impact multiple interconnected assets. Transportation decisionmaking systems need to incorporate these incidents rather than focus on one asset or issue (Park et al. 2021).

The FHWA Road Weather Management Program in the Office of Operations has produced numerous reports on road weather-responsive management strategies, mostly for extreme flooding events. For example, the report *Weather-Responsive Management Strategies (WRMS) – Agency Tools to Manage Infrastructure Impacts during Flood Events* highlights the efforts of many State DOTs in preparing for and responding to extreme flooding events (FHWA 2021). Of interest to this study, this report highlighted the use of UAV by the North Carolina and North Dakota DOTs in monitoring flood events (table 10).

Table 10: North Carolina U.S. Department of Transportation Unmanned Aerial Vehicle Flood Management Mission Types

Prevention and Preparedness (Before Flood Crests)	Response and Mitigation (During Flood Event)	Reconstruction and Recovery (After Evacuation Orders Are Lifted)
• **Strategic situational awareness, survey, and reconnaissance** • **Detailed or structural inspection**	• Strategic situational awareness, survey, and reconnaissance • Detailed or structural inspection • Ground or water search and rescue • Tactical situational awareness • Delivery	• Strategic situational awareness, survey, and reconnaissance • Detailed or structural inspection • Ground or water search and rescue

Source: FHWA 2021.

Another study, *Weather-Responsive Management Strategies (WRMS) for Flood Management in Iowa, Missouri, and Nebraska,* described the experiences and lessons learned from the Iowa, Missouri, and Nebraska DOTs as they managed major flood events in the Missouri River Basin (FHWA 2020c). The interesting perspective of this study was that the State DOTs used similar strategies but different tactics for flood management. Data sources and tools that were used differently by the State DOTs included river gauges, hydrologic modeling, LiDAR mapping, and different data repositories.

The literature also contained WRMS strategies about winter snow and ice (CTC & Associates LLC 2020). An FHWA report focused on MnDOT's use of WRMS approaches in expanding its use of road weather data and implementing WRMS-related applications that leverage the data to make more effective operational decisions (FHWA 2019a). A Web Maintenance Decision Support System (WebMDSS) leverages data from WRMS systems to provide recommendations for maintenance decisions, including the appropriate amounts of salt and other materials to apply to roadways. Snowplows provide images of road conditions that are shown on MnDOT's 511 traveler information system. The availability of mobile observations also allows the agency to better manage its vehicle fleet and assets during weather events. The reported MnDOT officials have stated that these capabilities, "result in safer roadways, increased mobility, reduced environmental impacts from salt use, and a reduction in agency costs due to less material usage and increased efficiencies with staff time." The use of cameras on snowplows is a topic that is found in numerous studies on winter maintenance (see, for example, Gallagher and Curd 2021). *Clear Roads*©, a group of several States that conduct testing of winter maintenance strategies, has sponsored much research on winter maintenance, including the use of WRMS strategies (2023).

Nonregulatory NCHRP Report 889, *Performance Measures in Snow and Ice Control Operations,* provides a synthesis of State DOTs' efforts to apply new technologies to improve managing winter operations (ICF et al. 2019). As noted in the report, "extreme weather, which dictates the level and nature of the snow and ice control response, requires a consideration of how risks and vulnerabilities are managed." A section of the report, "Advancements in Technology for Snow and Ice Control and Performance Measurement," described several of the technology applications that were active in winter operations management, in particular linking weather information to road conditions. The report noted that two of the most significant developments were the growth in deployment of AVL and the use of MDSS, stating,

> these technologies could potentially support data collection and processing, respectively, for multiple purposes such as treatment recommendations, route reporting, resource consumption tracking, and incident response, with the level of resolution influencing the extent to which the technologies can assist with decision-making needs (ICF et al. 2019).

Advances in pavement sensors, thermal mapping, and infrared sensors were also identified in the report as improving the ease with which data can be collected and analyzed.

With respect to WRMS technologies, the ICF report stated that the growth in the availability and use of weather and road condition data and products is a significant enabler of snow and ice removal performance measurement. The use of such data was reportedly used in maintenance and traffic decisionmaking in 47 (94 percent) of States responding to an FHWA survey (Gopalakrishna et al. 2016). Idaho DOT, Iowa DOT, Maryland DOT, Ohio DOT, and North Dakota DOT were highlighted in the report for their WRMS practices. The report also noted that stronger integration of the weather, traffic, and maintenance operations could lead to more responsive traffic management strategies such as weather-responsive traffic signal timing (Balke and Gopalakrishna 2013).

One of the emerging research technologies is examining how WRMS, automated vehicles (AVs), and connected vehicles (CVs) could be linked. Several studies in the FHWA WRMS series have examined the use of AVs/CVs as a means of collecting data on road conditions, weather, and traffic operations (Neumeister and Pape 2016, 2019). Kim and Mahmassani (2021) assessed the benefits of using data from CVs as input into a WRMS. That paper presented a framework for analyzing data in support of WRMS applications on CV-enabled road networks. Focusing on snowplow operations, strategies were developed to support operations' decisions. A test application connected to a prototypical network showed that the approach was effective in monitoring and managing snowplow operations and performance. Jiang et al. (2021) examined a similar application. That study used a segment of an I–80 Connected Vehicle Testbed in Wyoming under adverse weather conditions to simulate, evaluate, and assess two CV-based WRMS applications: traveler information messages and snowplow prepositioning.

Data

The ***importance of data availability and quality was one of the consistent themes in the literature and also in the interviews***. Data could include captured weather conditions, locations of potential impacts, the degree to which such conditions are creating hazardous situations on the road network, and the level of traffic that could be affected. Each of these datasets influence decisions on how to respond to potential hazards and, over the long term, action to take reduce or mitigate future disruptions. Table 11 contrasts 11 characteristics of traditional data management practices with their modern big data system/management counterparts (Klaver et al. 2020). Many

transportation agencies are still following what this table calls traditional data management practices when, in fact, WRMS approaches require a flexible and adaptive practice that reflects current best practice in the data industry. Klaver et al. noted that, "in no case can big data be managed effectively by simply adding more hardware or processing power to traditional methods; the nature of the data demands an updated approach" (Klaver et al. 2020).

Table 11: Traditional Data/System Management Approach Contrasted With Modern Big Data/System Approach.

Characteristics	Traditional Data System/Management	Modern Big Data System/ Management
System Design	Systems are designed and built for a predefined purpose; all requirements must be predetermined before development and deployment.	Systems are designed and built for many and unexpected purposes; constant adjustments are made to the system following deployment.
System Flexibility	System designed as "set it and forget it;" designed once to be maintained as is for many years. Systems are rigid and not easily modified.	System is ephemeral and flexible; designed to expect and easily adapt to changes. Detects changes and adjusts automatically.
Hardware/ Software Features	System features at the hardware level; hardware and software tightly coupled.	System features at the software level; hardware and software decoupled.
Hardware Longevity	As technology evolves, hardware becomes outdated quickly; system cannot keep pace.	As technology evolves, hardware is disposable; system changes to keep pace.
Database Schema	Schema on write ("schema first").	Schema on read ("schema last").
Storage and Processing	Data and analyses are centralized (servers).	Data and analyses are distributed (cloud).
Analytical Focus	80 percent of resources spent on data design and maintenance; 20 percent of resources spent on data analysis.	20 percent of resources spent on data design and maintenance; 80 percent of resources spent on data analysis.
Resource Efficiency	Majority of dollars are spent on hardware and software (requires a lot of maintenance).	Majority of dollars are spent on data and analyses (requires less maintenance).
Data Governance	Data governance is centralized; IT strictly controls who sees/analyzes data (heavy in policy setting).	Data governance is distributed between a central entity and business areas; data are open to many users.

Characteristics	Traditional Data System/Management	Modern Big Data System/ Management
Data	Uses a tight data model and strict access rules aimed at preserving the processed data and avoiding its corruption and deletion.	Consider processed data as disposable and easy to recreate from the raw data. Focus instead is on preserving unaltered raw data.
Data Access and Use	Small number of people with access to data; limits use of data for insights and decisionmaking to a "chosen few."	Many people can access the data; applies the concept of "many eyes" to allow insights and decision-making at all levels of an organization.

Source: Klaver et al. 2021.

Several research projects have focused on the linkage and integration of data sources on weather and road conditions as collected by a variety of means. As noted in the technology section, this research included new technologies such as UAV and AVs/CVs (Dey and Chowdhury 2015, McNamara et al. 2016, Tahir et al. 2022, Stepanova et al. 2020, Szirocza et al. 2022), applications on more traditional technologies (El-Rayes and Ignacio 2022, Gallagher and Curd 2021, ICF et al. 2019, Kim and Mahmassani 2021, Ozcan et al. 2020), as well as the analysis and display of data from more traditional technologies (FHWA 2020a, Gopalakrishna et al. 2016, Harrison et al. 2019, Jiang et al. 2021, Knickerbocker Sassani 2021, Sengupta and Walker 2020).

Interviews with State DOTs and Local Transportation Officials

As noted in the previous section of this report, 10 interviews were conducted as part of this study, 9 with State DOTs and one with a local DOT. The number of interviewees for each agency varied from one to eight. In most cases, district staff were part of the interviews, as were those representing maintenance, operations, and, in some cases, planning. Table 12 shows innovative technologies and practices identified during the interviews. Appendix B contains more detailed results of the interviews.

Table 12: Example Innovative Technology Use and Practices From Interviews.

Agency	Practices and Technologies Used
Arizona DOT	• 200+ cameras and AVL in snowplows tied into 511 system for public access • Dust storm detectors in one interstate corridor • River gauges to monitor water elevations • Post-wildfire burn scar monitoring in order to predict flood/debris flow • LiDAR data collection • NWS staff located at traffic management center • Resilience training of TMC staff

Agency	Practices and Technologies Used
Caltrans	• RWIS information used for staff and resource allocation • Cameras at key vulnerable locations tied to public websites • AVL and GPS use in snowplows • Gaming exercises for major flood events • Postfire burn scar monitoring for potential to create erosion and drainage blockage • Sustainability/climate adaptation leads created in each district • Adaptation/resilience plans for each district
Delaware DOT	• Prioritizing flood locations for adaptive action • Created State resilience funding program • Established resilience unit in agency • Road pavement sensors tied to road condition monitoring • Developing flood prediction models • High wind monitors on bridges • Formal process for considering equity • Policy for managed retreat in early stages of development
Florida DOT	• Bridge-mounted sonar devices in one district for monitoring flood elevations • River gauges used in other districts • Information from these sources used for staff allocations prior to and during storm events • Use of design criteria in vulnerable locations to raise road elevations • Use of tidal flooding sensors • Wind, fog, and snow/ice sensors used in parts of State with such exposure; tied to public warning systems
City of Houston Transportation Department	• Developing automated warning beacons for flood-prone roads based on cameras accompanied with sensors • Considering using automated physical barriers to prevent people from going into flooded areas • Piloting use of different types of materials to promote flood infiltration • Working with flood control departments/agencies to purchase repeat flood properties and use for water storage

Agency	Practices and Technologies Used
Iowa DOT	• Used statewide LiDAR data coupled with stream gauge data to determine whether assets will overtop due to flooding • Updated 511 system for flood events in order to provide clearer messages to those using the system • Used traffic cameras to investigate the level to which the surrounding areas are experiencing flooding or other damage-producing events • Established more threshold points when roads are to be closed • Considered allowing currently used predictive mapping of road conditions for maintenance forecasts available to the general public • Worked with the NWS office in Des Moines to incorporate transportation considerations in their messaging • Promoted maintenance vehicle navigation and obstacle avoidance systems for snowplows • Worked on enhancing the prediction of flooding using the National Water Model
Minnesota DOT	• Incorporated AVL technology as well as cameras in 400 snowplows; shared with the 511 system • Looking at historical data on more intensive plowing locations to locate snow fencing • Considering collecting automated and future road condition projections for truck movements and integrating traffic speed data with the RWIS data as part of the agency system operations database • Considering using RWIS data to better understand rain intensities that would be helpful in expediting repairs, as well as potentially in deciding on preemptive road closures • Using drones as part of a public information effort to show the extent of flooding and thus reinforcing the reasons for why roads are closed
North Carolina DOT	• Using geospatial data and GIS to help allocate resources (people and equipment) in the response and recovery phases post hurricane • Software used by every maintenance employee with a web-connected device to provide real-time live data; the survey includes damage information, pictures, etc. • Conducting a study to predict washouts • Studying use of predictive modeling of real-time water surface elevations • Developed real-time flood mapping showing the impacts to roads • Updating all types of sensors and gauge types; new gauges to monitor the potential for scour damage

Agency	Practices and Technologies Used
Texas DOT	• Rainfall gauges at 70+ weather stations used in real-time to estimate the degree to which heavy precipitation could cause serious flooding • Information integrated with existing traffic cameras and traffic monitoring systems and the Houston TranStar system and website to convey information to the traveling public • For expected flooding on I–10, deploying of rubber dams to prevent flooding • Response resources staged from coastline based on hurricane storm track • Drones used to inspect hard-to-reach bridges after extreme weather events. • Sensors embedded in the road to measure pavement temperature and wind
Utah DOT	• Hired 15 meteorologists and contracted with WeatherNet for an additional 13 • 80 road weather information system devices in State that inform traffic operations • Post-wildfire burn scar monitoring used to determine where erosion impacts could occur • Sensors have been deployed to monitor dust leading to proactive operational actions (e.g., warnings to travelers, proactively shutting down roads, etc.) • Developed risk priority maps across the state for pavement (roadways), bridges, and culverts, with potential threats being earthquakes, floods, debris flow, wildfire (contributing cause of debris flow), and extreme heat • Fire season forecasting informs mowing operations

The interviewees were asked to identify lessons learned from the application of these technologies and/or practices. Some of these lessons learned included the importance of taking the following actions:

- Integrate DOT efforts with the NWS for real-time weather prediction (the wildfire monitoring program was indicated as a good example); it is important to formalize the relationship (Arizona DOT).

- Develop partnerships and collaborations with a variety of groups that must be involved with a comprehensive winter operations program and other weather-related initiatives (several States).

- Prepare an action plan while waiting for research results. Recognize the value of talking to the maintenance staff and the local road users to understand issues and concerns so the action plan can be implemented in the near term (Delaware DOT).

- Consider that sharing data among a DOT’s own systems and with external dissemination is more complex than often envisioned. Challenges are often experienced in interpreting the data, and it was often difficult communicating how these challenges should be considered when disseminating the information to others (Florida DOT).

- Consider maintenance costs when reviewing technology options to employ (Florida DOT).
- Consider the scalability of a resilience strategy before implementing it. For example, the City of Houston has 2,000 plus traffic signals. A resilience program aimed at traffic signals would have to address all 2,000 (City of Houston 2023).
- Communicate carefully to the public forecasts that have a high probability of being wrong because a DOT does not want to “cry wolf,” but neither does it want to miss opportunities to communicate potentially adverse conditions (Iowa DOT).
- Maximize use of real-time information. Having up-to-the-minute information makes significant and noticeable differences on internal operations and public interactions. Make sure to translate the data to be digestible, so it is immediately “operational” for response and maintenance (North Carolina DOT).
- Value internal agency support for what is being proposed. It is useful to find examples of successful applications and share the stories. MnDOT has used meetings and forums in the highway district offices to share knowledge and experiences with winter operations (Minnesota DOT).
- Re-evaluate the use of return period flood events as an input for future, potential climate change threats (North Carolina DOT).

SYNTHESIS OF FINDINGS

The literature review and interviews highlighted some important observations concerning current and future characteristics of RWIS applications and resilience programs among DOTs. These observations are organized in this report into two major sections—technology and risk-based assessment.

Technology

The review of technologies used in RWIS, RWM, and MDSS indicate three major threads in the evolution of technology applications. The first uses sensors, imaging, and data collection technologies installed on current and traditional platforms, such as snowplows, traffic cameras, traffic signals, and the like. Although there are some challenges in using that technology (such as making the data collection streams compatible among the different functions of decisionmaking applications, generally the *research suggests that the challenges can be overcome with the application of current database management technologies and practices.* The literature review and interviews also indicated that *most of the State DOT attention on data collection is on flood monitoring and winter maintenance.* There were some other interests (e.g., Arizona and Utah DOTs’ interest in strong winds; Utah and Colorado DOTs’ interest in avalanches; NCDOT’s interests in mudslides), but the vast majority of the literature and interviews focused on flooding and winter maintenance.

Piggybacking on current and understood practices in State DOTs seems to be the major focus of many States. For example, the TxDOT interviews indicated that much of its road/weather strategy is based on expanding the agency's current flood monitoring strategy and on improving dissemination of information collected to stakeholders and to the traveling public.

The use of nontraditional technologies as data collection platforms is another notable characteristic of the literature. The most cited examples include the use of UAVs and AVs/CVs as a means of data collection. In the case of UAVs, this involved collecting meteorological data, road conditions, and the extent of an environmental hazard (e.g., the extent and severity of flooding). There seems to be great interest in using UAVs as a means of collecting data that are not necessarily found along the right-of-way. Indeed, the use of autonomous vehicle platforms for collecting data to be used in RWIS, RWM, and MDSS practices could very well be a major thrust in the industry. In addition, a Florida DOT official suggested that there is great potential for the use of artificial intelligence (AI) as part of a road weather management program, especially as it relates to flooding. He suggested that AI tools could predict where flood levels could reach critical thresholds given the characteristics of the storm. Also, AI could be used for predicting scour damage and potential wind impacts to key DOT assets such as bridges and signage.

The *interest in using AVs/CVs as probes for collecting data on road and weather conditions as well as traffic flows* and the effects of disruptions is not surprising. There has been great interest in the use of connected vehicles as probes in monitoring traffic conditions (e.g., congestion). Using vehicles for collecting data and information on weather-related disruptions is another extension of this perspective.

The literature and interviews do suggest that there is still a challenge in understanding how to connect weather and road condition data to make sense of what is happening at a particular location. This is primarily a matter of database management and would seem to be an issue that could be readily handled with evolving big data management platforms. This connection also reflects a concern on how to explain, especially to nontechnical audiences, what the information means. This concern was expressed in every interview. There was a considerable amount of literature on the use of dashboards and websites to convey advanced warnings to the traveling public.

Similarly, for a DOT, knowing "what is happening at a particular location" includes connecting real-time predictions of hazards to the actual physical damage (risk) to the asset; most of the information collected feeds into decisions relating to potential road closures. Few examples come close in determining whether more significant damage might occur. Important questions to DOTs could include: Will there be pavement delamination, embankment erosion, pier or abutment scour at a bridge, outlets scour at a culvert, etc.? To understand risk, the analysis should include some sense of damage potential. Including such information into real-time monitoring could be useful.

Risk-Based Assessments of Potential Climate Change and Extreme Weather Events

The literature review and interviews led to an important observation with respect to this project, one that reinforces the need for the tool that is being developed: *There are very few examples of quantitative, risk-based approaches or practices in support of transportation decisionmaking. This is particularly true for traffic and system operations.* The last 10 years have seen a lot of attention given to climate change and system resilience resulting in some early attempts at developing approaches and practices to inform decisions on where to most effectively invest to reduce the vulnerability of transportation assets to climate change-related threats. Although many of these approaches used “risk” when describing the approach, they were not quantitative risk-based approaches as defined in the literature and in other sectors. Most of the approaches were based on indicators of concern (e.g., low, medium, or high) and often color-coded to provide a visual key to the concern (green, yellow, and red).

Most of the literature relating to extreme weather, climate change, and transportation system resiliency, especially the earliest citations, provide general descriptions of potential threats and of possible strategies to minimize the threats. This is also true of those few studies that examined such threats to transportation system operations. For example, many of these studies concluded that extreme weather would disrupt traffic operations and that strategies to deal with such disruptions would reduce the amount of time road users would be delayed due to the disruptions. These types of conclusions did not help determine which strategies were most effective at reducing the amount of time road users would be delayed. The use of indicators in vulnerability and risk assessments does not provide the level of useful information that decisionmakers need to truly understand the tradeoffs being faced in developing the most cost-effective strategy.

Studies that define risk in monetary terms as the cost of disruptions, assuming no resilience improvements are made, are an important step in applying quantitative measures to risk. This approach is analogous to the practice in traffic safety of defining the risk (or benefits) of traffic safety improvements in terms of crashes (primarily fatal or with injury) that will occur without safety improvements.

Some of the early applications of these approaches defined costs foregone as being those occurring to the owner of the asset (State DOT) and to the users of the system (e.g., commuters, freight). The user costs have often been described as the extra time, vehicle operating costs, and potential safety impacts of taking detour routes around a disruption. More recently, some studies have added a concern for societal costs such as loss of emergency access, loss of connectivity to a region, and economic losses to regional inhabitants. However, in many ways, this more comprehensive approach is still in its infancy.

In general, the literature review and interviews suggest that there are still *gaps in understanding of risk-based planning and analysis*. That perception could become an even greater concern as States develop risk-based resilience improvement plans as part of the Bipartisan Infrastructure Law (Pub. L. No. 117-58) (FHWA 2023a).

Observations on Desired Capacity-building Strategies

Those interviewed identified a range of strategies for enhancing the capacity of agency staff to consider resilience in decisionmaking:

- Conduct peer exchanges among DOT staff in order to raise the understanding and knowledge about the challenges being faced, and importantly what innovative actions are being (and can be) taken.
- Provide more support for resilience training for State DOTs, focusing on operations, weather data availability, road weather information, etc.
- Disseminate information on new advances in climate projections.
- Increase support for nature-based solutions, providing more examples in coastal areas. In particular, highlight how such solutions can be paired with strategies to encourage economic development.
- Examine the greater use of connected vehicle data (not just traffic speed but wiper use and speed, etc.). This is a very quickly evolving data landscape and States need to keep an eye on this and potentially facilitate its development.
- Help build coalitions for data collection (e.g., weather data), and promote the application of new technologies in data exchange
- Encourage the development and application of performance measures for resilience, realizing that it will take time to develop and refine the data for performance measurement.
- Fund resilience pilot applications as they relate to operations and maintenance.
- Encourage pooled funding research on critical needs in RWIS and other weather-related challenges as they relate to operations and maintenance.
- Better coordinate agency resilience requirements/programs among Federal and State agencies.
- To the extent feasible within legislative constraints, provide more flexibility in the use of resilience funding.

APPENDIX A: INTERVIEW TEMPLATE

Interview Overview: FHWA Climate Resilience Risk Assessment Tool and Guide Project

Expected Length: Less than an hour

Focus areas

- Practices and technologies used to assess resilience to extreme weather and/or climate change for specific highway-system assets
- Emphasis on current examples of state-of-the-art/practice in risk mitigation tools and technologies for this topic area, potential challenges and gaps, insights on emerging technologies, and opportunities that can enhance risk assessment capabilities
- Methods for justifying investments in these items

Specific interest in:

- New technologies and/or approaches to monitoring and surveillance of weather conditions to provide the "context" for decision tools
- Monitoring, surveillance, and prediction of road conditions and operations given changing environmental conditions (e.g., through remote sensing or instrumented vehicles)
- New approaches for using this data and information in decisionmaking frameworks and traveler information systems, leading to weather-responsive management strategies
- Innovative approaches to roadway maintenance in the context of extreme weather and climate change
- In the context of longer term climate change, approaches that tie all of the above to future risks at each location/area/region
- Decisionmaking protocols and the historical context for justifying investment in the above technologies, methods, etc.

Questions

1) Please describe one or two advanced technologies and/or innovative practices in managing/planning for extreme weather or longer term climate risk, especially with respect to operations and maintenance of individual highway assets.
2) For each technology/practice you identified, please answer the following questions:
    a. Why did you adopt this technology/practice?

b. What changes or modifications have you made since adoption (if any)? Why were these changes made?

c. How has the technology/practice influenced both short- and long-term decisions in your agency? Please give examples.

d. What were the (approximate) up-front costs for adopting the technology/practice? Ongoing costs?

e. How were the costs justified when first proposing the technology/practice?

    i. Were risks with and without the technology/practice specifically quantified or otherwise characterized?

    ii. If so, did you find quantifying risks helpful to making a decision on a course of action? If not, do you think risk framing would be useful to justifying such actions?

f. Were alternative technologies/practices considered?

    i. If so, how were these evaluated in terms of tradeoffs with respect to effectiveness, cost, etc.?

    ii. Were risks to the asset quantified for each alternative? If yes, was this helpful? If not, do you think risk framing would be useful to justifying selection of a given alternative?

g. What are the lessons learned for other agencies dealing with similar issues and considering similar technologies/practices?

3) What gaps or challenges still remain to your agency in anticipating and responding to extreme weather disruptions and assessing their potential risks despite the technologies/practices just discussed? What are the characteristics of potential technologies/practices that could fill these gaps? Are there emerging technologies you are aware of that might fill these gaps?

4) What programmatic recommendations would you make to other transportation agencies interested in mitigating extreme weather and climate change risks?

5) Are you aware of any other agencies/researchers/vendors that are developing innovative approaches as described earlier that we should be aware of?

6) What recommendations would you make to encourage the development and implementation of advanced technologies and/or innovative practices in managing/planning for extreme weather or longer term climate risk?

APPENDIX B: INTERVIEW SUMMARIES

This appendix presents the results of the interviews, including descriptions of RWIS innovative practices and/or state-of-the-art practices, as well as a description of risk-based applications.

Arizona Department of Transportation (ADOT)

ADOT has implemented a wide-ranging program of RWIS and other weather-related strategies for safeguarding road operations and enhancing the safety of those using the roads. The agency's RWIS is collecting data every 10 minutes on pavement friction information and winds and feeding this information into traffic operations centers that, if necessary, convey information to road users via message signs and ADOT's Twitter feed. The intent is to use such data in operations decisionmaking. ADOT has mounted cameras on 200+ snowplows (started with four snowplows in a pilot 5 years ago) and shares the images with the public via the 511 program. ADOT is working on AVL technologies to better inform snowplow deployment planning. It was noted in the interview that no benefit/cost assessment was performed to justify the investment; it was assumed that the program is necessary to manage the state's highway network.

Arizona is known for extreme dust storms. ADOT received a $14 million grant to implement a dust storm detection system on I–10 between Tucson and Phoenix. As in other weather-related warning systems, the dust sensors are linked to road warning signs. ADOT also monitors agricultural fields near highways for dust potential; maps showing areas of highest concern are generated.

With respect to flooding, ADOT uses cameras at key locations to monitor flooding events. The agency uses some water elevation gauges, but cameras do most of the monitoring. ADOT is also tying into other camera systems (such as those used by municipalities).

The most comprehensive flood-related program focuses on the pumps to remove water from the roadway. Approximately 275 pumps primarily in the Phoenix area with many at the end of their useful life. As the roads were widened over the past decades, pump capacity was not upgraded "in a coordinated way;" therefore, many are now under capacity and do not meet the needs of particular locations. ADOT is currently using telemetry to report pump operations, but this method has not been reliable. The agency now adds fiber optics to the pump station network to obtain more reliable information on their functioning. ADOT uses historical precipitation data to identify needed improvements to the most at-risk pumps and to justify funding requests for their maintenance or replacement.

ADOT has also been active in examining post-wildfire burn scar in order to predict flood/debris flow that could affect State highways. ADOT staff has worked with the USGS to map all burn scars and rate each location by flood/debris flow risk. They are using radar to determine if critical rainfall thresholds are crossed and could result in serious debris flows. This approach has been successful in its accuracy of where flooding/debris flows would likely occur. It has been used to provide more efficient staff assignments.

ADOT also used the following technology and/or innovative practices:

- Use of drones and LiDAR to capture the landscape around bridges for bridge inspection to provide input into 2D modeling of the assets. In general, drones are not used very heavily because of the potential of their falling on the roadway and of privacy issues (95 percent of the right-of-way for state highways are leased from other entities).

- Geohazard mapping: ADOT has mapped all the geohazard locations of concern (landslides, rockfalls, and subsidence) and has implemented seismic and soil monitoring at key locations. Agency staff recommends annual LiDAR data collection for slope monitoring.

- GIS database of all known hazards: ADOT asked its maintenance staff to identify locations that are most likely to experience road disruptions due to weather or geohazard events. The data collected produced detailed information.

- Meteorologist coordination: The National Weather Service (NWS) staff have been added to the traffic operations center in Phoenix so that warnings can be made if predicted rain thresholds reach a certain magnitude.

- Resilience training for operations staff: ADOT provides annual training opportunities for its operations staff to enhance understanding of the importance of system resilience and to expose them to the latest RWIS and other approaches for providing a resilient road system.

An ADOT staff member identified the following gaps or challenges ADOT faces in anticipating and responding to extreme weather disruptions and assessing potential risks:

- Data management: An estimated 6 TB of climate data plus a great amount of real-time data are coming into ADOT from various sources. ADOT has been working with the State's universities to develop a strategy for handling these data but, so far, little progress has been made. The current strategy is to move some data to the cloud.

- Predictive capability of weather impacts: ADOT would like to have the capability to predict weather-related impacts and/or disruptions based on the data it collected.

- Staff with expertise on weather effects on the road system: According to the interviewee, having a dedicated full-time staff person to operationalize and manage a broader weather-related program would be helpful. Part of this person's responsibilities would be working with software vendors that are nontraditional to a State DOT.

With respect to recommendations for other States, the ADOT staff member emphasized the need to integrate State DOT efforts with the NWS for real-time weather prediction. The staff member emphasized the importance of formalizing the State DOT-NWS relationship and the value of establishing relationships with universities.

The ADOT staff member recommended more resilience training for State DOTs, focusing on operations, weather data availability, and road weather information. A model is TSM&O's

annual resilience training conducted at ADOT. This ADOT employee also recommended that the development of performance measures for resilience should be encouraged, realizing that it will take time to develop the data and refine it.

California DOT (Caltrans):

The Caltrans interview focused on winter operations and the use of RWIS information as reported through the WeatherShare platform[1] to manage agency actions. The approximately 180 RWIS stations monitor pavement temperature, precipitation, fog, wind, and dewpoint. These data inform decisions on staffing and equipment allocation. The historic data are useful in identifying locations that tend to have frequent pavement freeze. That information feeds decisions on equipment allocation and materials used.

Caltrans purchased truck spreaders used to spread brine at locations prior to snow/ice accumulations to buy time before plowing and to provide easy removal of snow and ice from high-risk locations. Caltrans officials noted that currently these locations are most often identified by maintenance staff. Cameras are also used at key points in the State highway network. Both the RWIS and camera information are used in public-facing changeable message signs.

Caltrans is experimenting with snow melter vehicle technology. Such a vehicle has been purchased and is being piloted in maintenance yards. The sense is that the vehicle would be most used in denser areas (e.g., around Lake Tahoe). Caltrans is conducting a benefit/cost analysis of the vehicle's use; expectations are that using the vehicle will provide a big reduction in man-hours, vehicle wear, and in greenhouse gas emissions relative to trucks hauling snow offsite.

Caltrans has also used AVL technologies for snowplows as well as using real-timemonitoring of snowplow operations. For example, data is collected on the treatment techniques used such as salt volumes and plow operating times. The intent is to interface this technology with operator timekeeping to save on data entry. Another example of the use of this technology is Caltrans' program for reopening mountain passes. A tablet is placed in a snowplow that uses GPS and a geocoded map of the State highway network to show where a plow is located with 8-inch accuracy. This technology enables plow operators to see where they are in relation to the edge of pavement, intersections, and guardrails. Caltrans is coordinating with ski resorts that have their own snowplows equipped with this technology to open roads affected by heavy snows.

Caltrans officials emphasized the importance of partnerships and collaborations with a variety of groups that must be involved with a comprehensive winter operations program. The agency initiated Operation Snowflake, which is a "war room" planning exercise with a variety of stakeholders (e.g., police, local communities, emergency responders) in the event of road

[1]See http://www.weathershare.org/

closures. The group considers different scenarios relating to extreme weather-related road closures. Oregon DOT officials are involved in the exercise for the northern part of California.

With respect to flooding, the California emergency operations center coordinates road closures and the release of public information. Coordination with NWS is critical. NWS officials are always the first to talk at strategy planning sessions for emergency operations. Flood predictions are based on gauged river levels and response plans provided for anticipated road closures.

For wildfires, Caltrans created burn area emergency response teams who examine postfire burn scars and their potential for creating future erosion and drainage blockage. The site examination is performed in coordination with the US Forest Service and the California Department of Forestry and Fire Protection to understand a particular burn scar and the hazards it could create. Value-at-risk (VARs) assessments are done after each fire and improvements/betterments are routinely applied (e.g., culvert expansion, debris basins, etc.).

Caltrans officials emphasized the benefit to the agency of having institutionalized climate adaptation in agency operations that includes adaptation/resilience as a core goal of the agency. Each of the districts has a climate vulnerability assessment with strategies identified for reducing climate change-related vulnerabilities. The newly created deputy director position leads sustainability/climate resilience efforts. Sustainability/climate adaptation leads have been created in each district. These efforts incentivised people to learn more about the topic.

With respect to how decisions are made to implement a new technology or practice, the Caltrans officials said that, generally, district staff get information on new technologies/practices and propose that headquarter staff consider investigating whether the technologies/practices would benefit Caltrans. They were not aware of any benefit/cost analysis analyses that were conducted and that, in most cases, a qualitative assessment on a system’s value was used. Caltrans belongs to the ClearRoads initiative,[2] and periodically receives ideas and information from this source.

With respect to gaps or challenges facing Caltrans relating to extreme weather disruptions and the ability of Caltrans to respond, the officials pointed to inadequate funding, especially when considering the magnitude of future climate change-related needs. It also pointed to the consideration of the environmental effects of adaptation projects themselves as a challenge. Caltrans interviewees thought the creation of a sustainability/climate resilience lead position in headquarters and each of the districts was an important strategy for advancing resilience work. Also, having adaptation/resilience plans for each district has been an important motivation for taking action. The Caltrans officials recommended that efforts should be made to mainstream resilience efforts within State DOT operations, including technical guidance, staff training, and increased funding.

[2]ClearRoads is a research program bringing together researchers and practitioners to improve winter road maintenance. See https://clearroads.org/ for more information.

Delaware DOT (DelDOT)

DelDOT has taken a keen interest in addressing flooding from storm surge, sunny day tidal flooding, and sea level rise. This is a particular concern to the agency because there are many coastal communities with only a single access road. As such, DelDOT officials identified several initiatives for monitoring frequently flooded roadways and for taking adaptive actions. DelDOT is in the process of developing a process for prioritizing locations where adaptive action will likely be necessary. Many locations that are frequently flooded are not eligible for Federal funding; therefore, DelDOT has to use State funds for prevention and rehabilitation efforts. Traffic volumes, first responder access and facilities, equity, and past experience with flooding (agency maintenance engineers were asked to identify locations of frequent flooding, which were placed in a GIS database) are part of the prioritization criteria. Agency officials estimate there are 200+ miles of frequently flooded roadways in the State.

The prioritization effort feeds into the agency's own capital program for resilience-focused projects. Delaware is one of the few States having a resilience-focused program and a corresponding unit within the agency. One of the early accomplishments of the program was the repaving of a frequently flooded road with permeable pavement (using funds from the resilience program) in addition to successfully encouraging the maintenance division to use special snowplow blades in order to prevent pavement damage. Having a resilience unit within the agency is unique among State DOTs. The program integrates well with other units in the State DOT as others see the importance of doing something about recurring flooding. One indicator of success is that the resilience staff (two members) are asked by others in the agency how to fund resilience work as part of project designs and construction.

Similar to other States, DelDOT has flood monitoring sensors on roadways and is working on developing a predictive modeling capability that will provide the agency with projections on where future flooding issues will likely occur. FHWA's State Transportation Innovations Council (STIC) funding has been used for monitoring flooding in certain locations. DelDOT has worked with the University of Delaware to develop low-cost monitoring technologies of water depths on the road, and this information is integrated with the outputs of USGS river/stream gauges. The predictive modeling will be used to update the public in real-time on current/future anticipated road closures. The agency is also working with Google (a State-designated technology partner) on reporting potential road closures to the public through Google's mapping/navigation systems. In general, DelDOT is investigating how to "push" more information out to the public in a way that is easy for a general audience to understand.

With respect to winter maintenance, DelDOT uses pavement sensors and monitoring software that uses pavement temperature to determine potential road ice locations. For high wind locations, certain bridges have wind monitors that provide information to warning signs for trucks using the bridges. The State police also request DelDOT to warn drivers and to change speed limits, using variable speed limit signs, when dense fog creates dangerous driving conditions. DelDOT is also developing a transportation resilience improvement plan (TRIP) to meet the Federal requirement for the agency's accessing Federal resilience funds (23 U.S.C. 176(e)(1)(B)).

The resilience unit is also developing approaches and methods for considering equity in its resilience work. Staff have evaluated various equity tools and are sponsoring efforts to get to a higher spatial resolution for data than is found in the Census data. This effort is in response to the Federal Justice40 initiative (USDOT n.d.). Part of this effort is to define environmental justice communities for which the State currently does not have a working definition.

The final topic discussed was the consideration of managed retreat (planned abandonment of infrastructure) for threatened areas where adaptation measures would be extravagantly expensive. DelDOT is starting the conversation because, unlike some other States, Delaware has areas threatened today. Many existing adaptation measures in some locations are near-term solutions; longer term, the agency may need to think about managed retreat. DelDOT offered an example of this concept. The road accessing the Woodland Beach community is flooded regularly. Per DelDOT, to elevate the road to prevent its being flooded would cost over $300 million. The community could be bought out and relocated many times with this cost.

When asked what lessons have been learned for similar applications in other States, DelDOT staff noted that one should not wait for a research project before taking action. It is important to talk to the maintenance staff and the locals to understand the issues and concerns and take action in the near-term.

DelDOT staff stated that the greatest gap or challenge in the agency's resilience program is predicting short duration, high-intensity storms (convective summer thunderstorms). In some cases, bridges have washed out, while nearby rain did not even fall on the road. As the staff noted, "We may never be able to predict everything, but trying to create systems/procedures that enable things to return to normal quickly requires some sense of what might happen."

DelDOT made the following recommendations for enhancing resilience capacity in State DOTs:

- Peer exchanges among State DOT staff are always helpful in raising understanding and knowledge about the challenges being faced, and importantly what innovative actions are being taken.
- More flexibility in funding is desired; earmarking to specific items can be limiting from the perspective of how to most cost effectively allocate funds to improve transportation system resiliency.

Florida DOT (FDOT)

Much of the discussion with Florida DOT officials focused on the agency's efforts concerning riverine, groundwater, and coastal flooding. For example, bridge-mounted sonar devices have been installed along the St. John's River and Intracoastal Waterway in District 2 to determine both water elevation at the device location as well as the upstream flood elevation of water that would be flowing downstream. These devices were first used during hurricane Ian for determining when SR 46 might reopen, which was closed due to flooding. They were also used to determine if the State's fixed rail transit line might be affected by flood levels. The sonar devices, which are located along the St. John's River, are accurate to within 1/2 inch of actual water elevation. There are 11 sensors. Currently, many of them are in rural areas. Information from the sensors is posted to an open website and also sent to the statewide monitoring system (https://icmstat.cflsmartroads.com/map/). FDOT has no plans to expand deployment in District 5 at this time, although other districts have expressed interest in possibly doing something similar. No formal analysis was conducted prior to installation; the sensors were installed at the primary locations of concern for flooding. The district representative estimated the costs of installation to be $50,000 per location and noted that providing power cables to each site was an expensive part of the installation.

Another district official noted that his district had been using river gauges at four locations for monitoring flood elevations. Previously the district manually measured the river water elevation using tape measures. The district had used drones for posthurricane assessments of flood waters and of damage to State facilities. The State Highway Patrol had recommended the deployment locations. The official estimated the cost of installation to be around $25,000 per location with most of the purchase and installation completed by FDOT staff. Float sensors and portable sensors were considered for obtaining river elevation data, but the agency concluded that having fixed locations enables it to establish a consistent datum and to compile historical information on river elevation.

Other flood-related monitoring efforts included using sensors for tidal flooding (to be applied in St. Augustine soon) (Smart North Florida n.d.); application of piezometers on a dry lake to monitor underground water pressure (to determine if water will rise from the lake); and adopting a design practice to build (when necessary) a roadway base at an elevation standard over seasonal maximum groundwater elevations (e.g., keeping a road base above 3 ft of the seasonal high groundwater elevation). If roadway base flooding cannot be avoided, FDOT considers the use of different pavement materials and design concepts that are meant to protect the road.

FDOT also uses sensors for monitoring wind, fog, and snow/ice. In Jacksonville, wind sensors attached to bridges capture wind speed/gusts. FDOT receives the captured information and distributes it to the public via FDOT's information systems. Similarly, fog sensors in Gainesville capture and transmit data about incoming fog to the FDOT information system as well as to warning signs at locations of high fog potential. District 3 in the Florida's panhandle placed snow/ice sensors on State bridges, including determining pavement temperatures using lasers and ice conditions from friction sensors.

Information collected from the different sensors is distributed via FDOT's information system. In addition, with respect to the flood sensors, the information is used to inform short-term operations—just prior to, during, and after a storm. Having the historical gauge/stage data helps inform the design of new projects.

With respect to the benefits associated with the application of different technologies, no formal benefit/cost analyses were conducted. As noted previously in this section of the report, FHWA expected that the District 2 sensor program would reduce the number of person-hours needed to monitor flood stages. Similarly, the district using river gauges concluded that overall, the district "saves money" by understanding river elevations and flood stage before and after high precipitation events.

FDOT officials noted several lessons learned from their road weather management efforts. First, data sharing among FDOT's own systems and with external dissemination was more complex than envisioned. Second, challenges were experienced in interpreting the data, and it was often difficult to communicate how these challenges should be addressed when disseminating the information to others. Third, it is important to consider maintenance costs when thinking about evaluating technology for employment. Fourth, start small and build up a system of monitoring as you become more familiar with the technology and its requirements. Finally, care should be given about how to share the information to other stakeholders (e.g., the State Highway Patrol, emergency management officials, and the media).

FDOT officials identified several gaps in the agency's abilities to anticipate and respond to extreme weather events. The following is a list of the gaps:

- Sunny day tidal flooding tracking in South Florida. The agency thought of using cameras along Route A1A to track such flooding.

- A need for more finer grained, real-time monitoring systems (i.e., micronetworking) that will permit more detailed assessment of dangerous locations.

- A need to have better internal communications about all the efforts to provide real-time monitoring (e.g., the Flood Hub at the University of South Florida is working on real-time inundation mapping, which needs to be better integrated with FDOT's activities).

- Flood prediction, scour damage prediction, and the identification of potential wind impacts on road users and on some of FDOT's assets (e.g., signage). Artificial intelligence (AI) applications might be able to address this gap.

- A need for better coordination with Alabama and Georgia on flood prediction (most water in northern Florida originates from the north and flows south).

FDOT officials identified several in-State universities that are conducting research that might be of interest to the climate resilience risk assessment tool project. The Flood Hub at the University of South Florida, which includes Florida International University, the University of Miami, USGS, and several other participants, holds promise for some interesting tools and approaches. Having just recently been formed, the Flood Hub will be producing tools for estimating real-time flood mapping, future precipitation mapping, and evaporation rates for flooded areas. The University of Central Florida is also involved in weather-related research.

With respect to recommendations for enhancing State DOT resilience capacity, FDOT officials suggested that peer exchanges are a very good way of fostering adoption of new technologies or approaches. Gathering best practices from across the country and from private industry would be very helpful. With respect to the technical approach for considering extreme weather in State DOT decisionmaking, the concept of dynamic adaptive policy pathways should be encouraged whereby adaptations are implemented incrementally as conditions warrant according to a pre-established management plan. It is also important to have better knowledge on the overall impacts of back-to-back extreme weather events as well as the impact of antecedent moisture in the ground on flood levels.

City of Houston, Transportation Department

Houston has faced flooding throughout its history, aggravated by the fact that the city is very flat. The city's Transportation & Drainage Operations service area within the Department of Public Works is responsible for traffic operations, roadway maintenance, and stormwater operations. Staff members noted that the combined title of the service area is notable in that many of the city's roads are designed to be used for flood storage (secondary system in most cases, primary in some). The goal is to remove the water from street storage as soon as possible. In this regard, the staff mentioned that an open ditch drainage system actually performed better than a closed stormwater system because a closed drainage system gets clogged and requires pumps that can become nonfunctional in power outages.

Houston is developing automated warning beacons for flood-prone roads, where the locations for the beacons are where injuries/fatalities could occur, that is, where higher water depths are likely. The expectation is that this program will be implemented over the next 2 years. The system might be integrated with TranStar, a regional traffic operations center and information program. The monitoring approach will include cameras accompanied with sensors that can estimate flood depths. This information will be fed into a central command center with feeds into first responders so they can understand conditions they might face. City staff noted that this technology was not necessarily at the forefront of technology, but the city's intent is, in fact, to use mature technology. City officials are considering using automated physical barriers to prevent people from going into risky areas when the warning signs are triggered. Staff said that they had considered the use of drones for flood monitoring but were concerned about battery limitations that prevent long-term use. Therefore, drones were not considered reliable enough for this purpose.

The city is also piloting use of different types of materials to promote flood infiltration, such as permeable pavement. The following list shows other initiatives under consideration by the staff:

- Using low-cost soil preparation to encourage permeation given that impermeable clay soils underlies much of the city
- Piloting two "green streets" that will integrate with the open ditch drainage system
- Investigating the maintenance needs of these approaches through pilot applications
- Using automated monitoring for water quality changes, but not for flood reduction, which will be assessed in person
- Water storage solutions such as developing a toolkit with the Parks Department for water storage. For example, there is a proposal to lower the elevation of five recreational fields so they can be used for back-up water storage.
- Working with flood control departments/agencies to purchase repeat flood properties and use them for water storage

- Exploring use of prairie grasses in the open drainage ditches which might encourage better infiltration

City officials are trying to work resilience strategies into the bridge program by recommending incremental bridge resilience actions during bridge reconstruction. However, with only 4 bridges reconstructed each year, out of 1,600 bridges in the city, this approach will not have a significant effect on the network's overall resilience for some time. City staff are looking at including resilience into the city's project prioritization process, even if bridge condition and functionality do not require the asset to receive immediate attention.

With respect to gaps or challenges to the city's resilience efforts, staff noted the need for a model that looks at the cumulative effects of both development and infrastructure on flooding throughout the city. Modeling is piecemeal at this point, performed property-by-property.

Other agencies considering similar resilience approaches gave the following recommendations:

- Water knows no boundaries; look beyond the right-of-way. This action requires coordination with several different city agencies and other entities throughout the region. It also leads to the question: Who can hold water on their properties?

- It is important to maximize integration with existing drainage and compatible (such as recreation) systems.

- Although not always considered an issue with flooding, cybersecurity can be important when integrating with operations systems like Houston TranStar. For example, when Houston suffered massive power outages due to an ice storm, its drainage water pumps did not work.

- It is important to consider the scalability of whatever resilience strategy one adopts. For example, the city has 2,000 plus traffic signals. A resilience program aimed at traffic signals would have to address all 2,000.

A strategy can be to incorporate resilience needs into all grant/funding programs, either as a stand-alone funding program or by allowing resilience actions to be an add-on cost.

With respect to recommendations for agency capacity enhancement, city officials recommended that any benefit/cost analysis tool for resilience projects include costs relating to operations, implementation, and training associated with the adaptation measures under consideration.

Iowa Department of Transportation

The Iowa DOT has used statewide LiDAR data coupled with stream gauge data to determine whether assets will flood. The agency initiated LiDAR collection for other purposes, but it was able to repurpose it for the prediction of overtopping. The use of newly collected LiDAR was important because historical data do not reflect changes in land use that occurred over time; consequently, it provides a truer sense of potential flooding impacts than historical data alone. LiDAR data was used in 2019 when the Missouri River flooded, and parts of the interstate system were underwater for months. Iowa DOT officials noted that this capability can also be used for several purposes:

- Planning operational measures like road closures and sandbagging as long as projections are provided at least a day in advance
- Locating where no recent flooding occurred but there is future flood potential
- Mitigating risk related to both keeping the road functional and preventing damage
- Locating where to build a temporary berm to prevent flooding. This use requires lots of lead time to implement and is most suitable for high traffic locations or where there are long detours.

The officials noted that the capability has become standard operating procedure for use statewide. Other technology practices they noted included the following list:

- Updated 511 system for flood events in order to provide clearer messages to those using the system
- Established more threshold points when roads are to be closed, while also providing web-based maps for flood closures
- Used traffic cameras to investigate the level to which the surrounding areas are experiencing flooding or other damage-producing events
- Considered allowing currently used predictive mapping of road conditions for maintenance forecasts to be available to the general public
- Automated road condition reporting, e.g., winter weather, flooding.
- Provided short-term predictions (3–6 hours) showing whether the State DOT expects the conditions to get better or worse. Wisconsin and Minnesota DOTs have started work on such a system for winter weather and are trying to determine if the information is viable for public consumption and how to package and message it to the public to avoid information overload.
- Worked with the NSW ice office in Des Moines to incorporate transportation considerations in their weather messaging
- Promoted maintenance vehicle navigation and obstacle avoidance systems for snowplows
- Worked on enhancing the prediction of flooding using the National Water Model (NOAA, n.d.)

With respect to the effects of these approaches on agency decisionmaking, the officials noted that short-term operational responses like closing roads and temporary flood control measures have been undertaken. For long-term operational responses, many of the roads that overtopped have been elevated; however, some overtopped again even after being elevated.

Iowa DOT officials identified the following gaps or challenges in anticipating and responding to extreme weather disruptions and assessing their potential risks:

- An important challenge is putting forecasts out to the public that have a high potential to be wrong. Iowa DOT does not want to "cry wolf," but neither do they want to miss communicating potentially adverse conditions they know about. There needs to be a balance. Forecasting those types of conditions is particularly challenging because, internally, there are more sophisticated users of the data who understand the nuance and uncertainties involved in forecasting, but the general public does not necessarily have this perspective or level of technical understanding.

- Uncertainty affects flood predictions, e.g., the LiDAR-based flood mapping. Long lead times benefit preparation but increase uncertainty about accuracy of the forecast.

- Disseminating information effectively is also a challenge. For example, how can a forecaster communicate to people who are traveling long distances and coming into the State?

- Inspections are needed to identify and evaluate sinkholes and scour. That data must be collected and scoped out before reopening of a closed road. Even though scour prediction models can hasten that activity, the structure still remains shut down during the inspection.

With respect to programmatic recommendations for other State DOTs interested in mitigating extreme weather and climate change risks, the Iowa DOT officials identified the following:

- Focus on communications and in establishing standard operating procedures. Develop relationships with key players ahead of time. For example, coordinate with IT on software updates so they do not happen when big weather events are expected.

- Establish close partnerships. For example, Iowa DOT has close partnerships with motor vehicle safety, Homeland Security, and other agencies. In particular, protocols were put in place so that everyone understands what is going on and what their roles are.

- Investigate the use of social media to raise awareness

- Invest in the data and tools (like LiDAR) that allow information to be leveraged among other uses within the agency

Iowa DOT officials made the following recommendations for enhancing State DOT capacity for considering resilience in decisionmaking:

- Examine the greater use of connected vehicle data (not just traffic speed but wiper use and speed, etc.). This is a very quickly evolving data landscape.

- Roundtables and peer exchanges are very helpful; can be informal

Minnesota DOT (MnDOT)

Given its northern location, MnDOT has been concerned about winter operations for many decades, and, accordingly, has implemented a range of RWIS applications. The agency has incorporated AVL technology as well as cameras in 400 snowplows. The images from cameras and RWIS data are shared with the 511 system, and MnDOT is looking at more ways to enhance the use of this information. Pavement and air temperature sensors and friction monitors on snowplows are also collecting data on road conditions that is shared with the agency operations and the traffic operations center in the Twin Cities region. The agency has used the information from these various sources to plan winter storm event response for road plowing. MnDOT is also looking at the historical data on locations where intensive plowing seems to occur regularly from the perspective of locating where snow fencing might be necessary.

With respect to the costs associated with this winter operations program, MnDOT staff estimated that it cost the agency about $3,500 per snowplow for AVL application with approximately $45 per month per plow for ongoing data collection. Systemwide, the agency estimated it spent $15–20 million for the RWIS stations around the State. MnDOT staff noted that the justification for the expenditure of these funds was related to the question of how to define a successful treatment program that can become a baseline for making improvements over time. The focus of winter maintenance improvements is all about gaining efficiency in operations.

The agency is considering collecting automated and future road condition projections for truck movements and integrating traffic speed data with the RWIS data into the agency system operations database. In addition, agency staff are considering using RWIS data to better understand rain intensities that would be helpful in expediting repairs, as well as potentially in deciding on preemptive road closures.

MnDOT is using drones for many different agency tasks, including as part of a public information effort to show the extent of flooding thereby reinforcing the reasons for road closures. Given Minnesota's frequent severe weather conditions, drones cannot be used during the worst storm events.

In terms of lessons learned from its winter operations experience, MnDOT staff noted that it is important to determine how they want to use the data being collected before implementation of any data collection program. It is important to have internal agency support for what is being proposed and is useful to find examples of successful applications and "share the stories." MnDOT has used meetings and forums in the highway district offices to share knowledge and experiences of winter operations. It is important to anticipate possible issues and develop a strategy for dealing with them. MnDOT staff noted that success will include developing a team with broad capabilities. For MnDOT, those capabilities must include not only typical maintenance expertise but also knowledge of meteorology and sustainable treatments.

With respect to recommendations for enhancing State DOT capacity, MnDOT staff suggested that more collaborations with Federal and State agencies would be valuable, especially in fostering knowledge-sharing and exchange of experiences. For example, the staff suggested that building coalitions for data collection (e.g., weather data) would be worthwhile and could promote the application of new technologies in data exchange.

North Carolina DOT (NCDOT)

NCDOT is pursuing one of the more comprehensive applications of resilience strategies with respect to road/weather practices. Not surprisingly, given the State's experience with hurricanes, the State DOT officials noted that they conducted a "deep dive" on past experiences with hurricanes and investigated where damage occurred and the reasons for the damage. For example, hurricanes Mathew and Florence largely affected the same parts of the State, so NCDOT examined how repairs from the earlier storm stood up to the second storm. The effort focused on bridges and culverts/pipes. In addition, NCDOT is using geospatial data and GIS to help allocate resources (people and equipment) in the response and recovery phases post hurricane. Survey 123 (an Esri product) is being used by every maintenance employee with a Web-connected device to provide real-time data; the survey includes damage information and pictures. This practice speeds up response and recovery, helps with stakeholder outreach, and leads to a coordinated response in seeking Federal support. Other practices identified by the NCDOT officials include the following list:

- NCDOT is conducting a study to predict washouts, working cooperatively with NC State University and SAS Institute, a firm that specializes in analytics, artificial intelligence, and data management. The focus is on three river basins and, in particular, identifying more resilient paths through the road network.

- Another study being conducted on I–95 and US 74 is the use of predictive modeling of real-time water surface elevations. The results could help define the low chord elevations of bridge decks during design.

- NCDOT has developed real-time flood mapping showing the effects to roads. Mapping is already available for the eastern and western parts of the State. The agency is now mapping the rest of the State. For coastal hazards, the effort uses the Advanced CIRCulation model storm surge data from the University of North Carolina that shows predictive exposures and depths. The data is being used in real-time for operations and emergency responses, an effort coordinated with the North Carolina Emergency Management Agency. The Coast Guard is also using the results of this effort for its storm planning.

- NCDOT is also updating all types of sensors and gauge types. The agency is concerned about scour potential at piers; therefore, monitoring equipment has been installed on a bridge in the Outer Banks. Dozens of new gauges are being put in place to monitor the potential for scour damage.

NCDOT officials identified the following gaps or challenges in their resilience program:

- Need information on the timing and duration of flooding due to storm surge. The current tool just indicates the areas that will get wet sometime during the storm.

- Because bridges could lose spans due to wave impacts, real-time bridge flood monitoring software needs to add surge and wave action. This type of software is currently used by NCDOT.

- Leverage the National Water Model to fill the gaps in the stream gauge network. The riverine model only considers 5 miles up and downstream from each gauge.

- Focus coastal model developers on compound flooding (combination of storm surge flooding and riverine flooding), which is a key issue for coastal flooding because many towns are at the end of the estuaries.

- Include pluvial flooding, overland flooding outside a river (ponding), in the RIT floodway inundation tool as pluvial flooding was a major issue with past hurricanes in North Carolina.

With respect to programmatic recommendations for other State DOTs, NCDOT officials recommended the following:

- Maximize use of real-time information. This makes a significant and noticeable difference on interacting with internal operations and the public. Need to make sure the data are translated to be digestible and that they are "operational" for response and maintenance.

- Consider reevaluating the use of return period flood events as an input into future potential climate change threats.

With respect to State DOT resilience capacity enhancement, NCDOT officials recommended the following actions:

- Look at the full spectrum of risks and extreme weather. For example, NCDOT is looking at flooding, heat (on pavement), and geohazards.

- Stay abreast of new advances in climate projections.

- Improve coordination among Federal agencies on resilience requirements/programs. Rule changes are often confusing. For example, FHWA allows betterments to enhance resilience in Emergency Response projects, but that action conflicts with Federal Emergency Management Agency damage declaration guidance that assumes in-kind replacement.

- Increase support for nature-based solutions providing more examples in coastal areas. In particular, highlight how such solutions can be paired with strategies to encourage economic development.

Texas Department of Transportation (TxDOT)

TxDOT officials identified the regional flood warning system, covering the Houston and Beaumont metropolitan areas (with extension to Corpus Christi planned next), as a good example of a weather/road condition example. Rainfall gauges at 70+ weather stations provided by the Harris County Flood Control District are used in real-time to estimate the degree to which heavy precipitation could cause serious flooding (1 inch in 15 minutes is a threshold for concern). This information is integrated with existing traffic cameras and traffic monitoring systems and the Houston TranStar system and website are used to convey information to the traveling public (there is also an app). This information is also tied to traffic signals in the event that some roads must be closed.

Other uses of weather-related information and corresponding responses included the following:

- For expected flooding, TxDOT can deploy rubber dams along portions of I–10 to prevent flooding on this critical supply route.
- Preparations are staged by distance from the coastline based on hurricane storm track.
- Veoci software is used for emergency management.
- TxDOT Emergency Response App (TxERA) software is used for monitoring emergency vehicle locations.
- Drones are used to inspect hard-to-reach bridges after extreme weather events. Five different models were purchased and tested before making the final purchase.
- An ice warning system is being developed.
- Sensors are embedded in the road to measure pavement temperature and wind. These are typically placed after paving has been done.

With respect to how these practices have influenced decisionmaking within the agency, the flood management system is used routinely for operations decisions and emergency response by all stakeholders in the region and the general public. TxDOT is also using the practice for determining when contraflow lane operation might be necessary during hurricane evacuation.

The decision to implement these practices did not really go through a formal benefit/cost analysis (except for the TranStar system). Risk was not quantified and thus was not used to justify the flood monitoring program. The practices developed in response to existing problems and were based on lessons learned from past flooding events.

Two lessons were identified from the flood monitoring system: (1) the need for battery back-ups for the system, including for the traffic signal system, and (2) the need to use the system to prevent people from traveling into dangerous areas, if possible.

With respect to programmatic recommendations, the TxDOT officials identified the following two as being the most important considerations:

- Avoid using just one system, especially if one is proprietary.
- Understand you will not necessarily have the resources to build the system all at once; lay out a vision and roll it out over time as resources become available.

TxDOT officials recommended that grant programs for implementing resilience technologies would encourage States to adopt such technologies as part of their programs.

Utah Department of Transportation (UDOT)

UDOT officials identified the following innovative road/weather practices and/or technologies that they have used in their agency:

- The agency hired 15 meteorologists and contracted with WeatherNet for an additional 13. The agency's rationale is that having its own meteorologists provides staff with greater knowledge on how weather events can affect the highway network. Computer-based predictive models have not worked well in Utah's complex topography. Human meteorologists are better at predicting at this time.
- There are 80 road weather information system devices around the State that inform traffic operations but do not feed into maintenance decisions. Weather stations have cameras to validate precipitation falling. There are several gaps in radar coverage around the State. UDOT has assessed historical data from the devices and uses it to inform near-term predictions of road weather conditions. Twenty-four to 36-hour forecasts of winter weather conditions are used.
- Postwildfire burn scar monitoring is used to determine where erosion effects could occur. After a recent wildfire, precipitation monitoring was performed and compared with thresholds for mudslides to occur (0.1 inch of rain in this case). UDOT is currently monitoring 12 burn scars but plans to expand the program. Effects of burn scars usually last about 5 years for hydrologic considerations, longer for avalanche concerns. UDOT is also working with the NWS to determine ways to message possible threats. The agency is planning to give alerts to the maintenance department of potential issues so emergency contracts for repairs can be expedited. This knowledge and tracking of past effects will help UDOT proactively mitigate potential risks with funds from the Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT) program.
- Monitoring blowing dust has been a concern in some parts of the State. About 10 years ago, a major incident occurred involving blowing dust. Last year eight people died due to blowing dust from a feed lot. Off-highway vehicle areas can disturb the soil, on holiday weekends especially, resulting in blowing dust issues. If soil moisture is less than 10 percent and if there is soil disturbance, blowing dust can cause major issues. Sensors have been deployed to monitor for dust density in the air. Excessive dust leads to

proactive operational actions such as warnings to travelers and proactively shutting down roads.

- UDOT has developed risk priority maps across the State for pavement (roadways), bridges, and culverts, with potential threats being earthquakes, floods, debris flow, wildfire (contributing cause of debris flow), and extreme heat. The risk variable is the cost of disruption to these assets (user costs and owner costs) due to one or more hazard. This information has been used to prioritize adaptation actions in the agency. The map shows 179 culverts in floodplains that may be at high risk, such as potential overtopping. The agency is leveraging historical data from the real-time monitoring stations to inform this process. The map considers asset criticality (e.g., AADT, truck traffic, and sole access route).

- Fire season forecasting informs mowing operations; that is, efforts are made to keep right-of-way grass short. These practices were primarily motivated by a concern for traffic safety and an expected long-term trend towards more impactful fires.

- The agency believes that developing a past record of hazards could eventually lead to design changes (adding hydraulic capacity, slope armoring, etc.).

With respect to the consideration of quantified risk prior to investing resources to undertake the practices described above, there was little analysis. In one case, back-of-envelope calculations were used to estimate benefits from applying resilience strategies that considered traffic volumes and detour lengths. The RIP will necessitate more standardization of this risk assessment using benefit/cost analysis. The UDOT officials emphasized that adaptation options need not always be capital improvements; they could include operational/maintenance actions that also reduce risk (or, at least, lessen recovery times).

With respect to gaps in current practice, UDOT officials noted the following:

- Need to improve forecasting models to work with the complex terrain in Utah

- Need for a better understanding of extreme temperature projections vis-à-vis critical thresholds of assets

- Should the agency use a range of likelihoods for projections rather than just a specific single value probability? Note that weather forecasters at the Utah DOT do not typically provide probabilities of extreme weather events occurring.

- Forecasting of heavy precipitation from convective storms over relatively small areas is very limited; some of the highest damage relates to the resulting flash flooding.

With respect to programmatic recommendations to other State DOTs interested in mitigating extreme weather and climate change risks, UDOT managers made these recommendations:

- Hire meteorologists or somebody who can interpret the NWS forecast for the State DOT as it relates to transportation assets. Several State DOTs do not have meteorologists.

- Disseminate resilience/adaptation knowledge throughout the organization. UDOT is a lean agency, so there is no budget to stand up a stand-alone resilience team. Need to disseminate the resilience knowledge so everyone in the agency becomes a resilience practitioner.

The UDOT officials made the following recommendations to support the road/weather resilience initiative:

- Promote resilience pilot programs as they relate to operations and maintenance. NCHRP is doing this more with “ambassador State DOTs” to work with implementing the ideas in its reports.

- Encourage pooled funding research on critical needs.

GLOSSARY

Adaptation Decisionmaking Assessment Process (ADAP): Considers climate change-related risk during project development in a systematic way. ADAP is intended as "a risk-based tool to aid decisionmakers in determining which project alternative makes the most sense in terms of life cycle cost, resilience, regulatory and political settings, etc." (FHWA, 2019b).

Maintenance Decision Support Systems: A computer-based, customizable tool that provides winter maintenance personnel with route-specific weather forecast information and treatment recommendations (FHWA n.d.).

Managed Retreat: The transition of "people, communities, infrastructure, and ecosystems away from areas vulnerable to frequent extreme weather and climate change impacts" (Sniffen et al 2021).

Resilient Project: "A project with the ability to anticipate, prepare for, or adapt to conditions or withstand, respond to, or recover rapidly from disruptions, including the ability to resist hazards or withstand impacts from weather events and natural disasters; or to reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters" (FHWA 2023a).

Risk Management: Identifying and responding to the inherent uncertainties of managing a complex organization through a process of analytical and management activities related to finances, asset condition, and climate change (Jacobs Engineering et al 2022).

Road Weather Information System (RWIS) and *Road Weather Management (RWM) Systems*: "A Road Weather Information System (RWIS) is comprised of Environmental Sensor Stations (ESS) in the field, a communication system for data transfer, and central systems to collect field data from numerous ESS. These stations measure atmospheric, pavement and/or water level conditions" (FHWA 2022).

StreamStats: USGS tool that provides "access to spatial analytical tools useful for water-resources planning and management, and for engineering and design purposes. The map-based user interface can be used to delineate drainage areas, get basin characteristics and estimates of flow statistics" (USGS n.d.).

Transportation Engineering Approaches to Climate Resiliency (TEACR) Study: FHWA study that applied the ADAP process for project development for different types of assets and for different climate stressors (FHWA 2023b).

Transportation System Management and Operations (TSM&O): A set of strategies focusing on operational improvements that can maintain and restore the performance of the existing transportation system before extra capacity is needed. The goal is to get the most performance out of the transportation facilities already in place (FHWA n.d.).

Weather-Savvy Roads Program: FHWA initiative focusing on issues caused by weather impacts on the transportation system by, "promoting two innovative road weather management solutions: Pathfinder and Integrating Mobile Observations (IMO). Pathfinder provides a step-by-step process for building relationships with partners to share forecasts and road conditions, and then provides consistent messaging to travelers. IMO involves enhanced data collection from agency fleet vehicles to improve awareness of road conditions" (Pisano 2019).

REFERENCES

Abdelraouf, A., M. Abdel-Aty, and Y. Wu. 2022. "Using Vision Transformers for Spatial-Context-Aware Rain and Road Surface Condition Detection on Freeways." *IEEE Transactions on Intelligent Transportation Systems* 23, no. 10: 18546–18556. https://ieeexplore.ieee.org/document/9716073#citations, last accessed May18, 2023.

American Association of State Highway and Transportation Officials (AASHTO). "Guidance to Improve the Effectiveness of Your TSM&O Program" (web page). http://www.aashtotsmoguidance.org/, last accessed May 18, 2023.

Armstrong, A., M. Flood, and M. Meyer. 2014. "Development of Adaptation Framework for Climate Change Engineering Assessment of Transportation Assets." Presented at the International Conference on Sustainable Infrastructure 2014. https://doi.org/10.1061/9780784478745.014, last accessed May 18, 2023.

Asam, S, C. Bhat, B. Dix, J. Bauer, and D. Gopalakrishna. 2015. *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance*. Report FHWA-HOP-15-026. Washington, DC: FHWA. November. https://ops.fhwa.dot.gov/publications/fhwahop15026/index.htm, last accessed June 6, 2023.

Balke, K. and Gopalakrishna, D. 2013. *Utah DOT Weather Responsive Traffic Signal Timing*. Report FHWA-JPO-13-088. Washington, DC: FHWA.

Boselly, S.E. 1992. "Benefit-Cost Assessment of the Utility of Road Weather Information Systems for Snow and Ice Control." Transportation Research Record 1352. https://onlinepubs.trb.org/Onlinepubs/trr/1992/1352/1352-010.pdf, last accessed June 6, 2023.

Colorado DOT. 2017. *I-70 Corridor Risk & Resilience Pilot, Denver, CO. Final Report.* Denver, CO: Colorado Department of Transportation. https://www.codot.gov/programs/planning/assets/plans-projects-reports/reports/i70rnr_finalreport_nov302017_submitted_af.pdf, last accessed May 18, 2023.

CTC & Associates LLC. 2020. Resources, Practices and Needs for Weather Forecasting to Facilitate Winter Road Maintenance: Synthesis Report. Clear Roads Project CR19-S2, Dec. Accessed at https://clearroads.org/wp-content/uploads/dlm_uploads/FinalReport_CR.19-S2_Dec2020.pdf, last accessed June 6, 2023.

Culp, M. and EV0101, T.N., 2009. Literature Review: Climate Change Vulnerability Assessment, Risk Assessment, and Adaptation Approaches. FHWA. Accessed at https://www.cakex.org/sites/default/files/documents/Vulnerability%20Assessment%20-%20FHWA.pdf, last accessed June 6, 2023.

Dewberry Engineers, Inc., Venner Consulting, Inc., Impact Infrastructure, Inc., and McVoy Associates LLC. 2020. *Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change Guidebook.* NCHRP Report 938. Washington DC: Transportation Research Board. https://nap.nationalacademies.org/catalog/25744/incorporating-the-costs-and-benefits-of-adaptation-measures-in-preparation-for-extreme-weather-events-and-climate-change-guidebook, last accessed June 6, 2023.

Dey, M. and Chowdhury. 2015. "Potential of Intelligent Transportation Systems in Mitigating Adverse Weather Impacts on Road Mobility: A Review. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 16, Issue: 3, June, Page(s): 1107–1119. Accessed at https://ieeexplore.ieee.org/document/6991566, last accessed June 6, 2023.

Dorney, C., M. Flood, T. Grose, P. Hammond, M. Meyer, R. Miller, E. Frazier, Sr., J. Western, Y. Nakanishi, P. Auza, and J. Betak. 2021. *Mainstreaming System Resilience Concepts into Transportation Agencies: A Guide*, NCHRP Report 970. Washington, DC: Transportation Research Board. https://nap.nationalacademies.org/catalog/26125/mainstreaming-system-resilience-concepts-into-transportation-agencies-a-guide, last accessed June 6, 2023.

El-Rayes, K. and E-J. Ignacio. 2022. *Evaluating the Benefits of Implementing Mobile Road Weather Information Sensors,* Series Issue Number: 22-004, Civil Engineering Studies, Illinois Center for Transportation, University of Illinois, Feb. https://doi.org/10.36501/0197-9191/22-004, last accessed June 6, 2023.

Ewan, L., and A. Al-Kaisy. 2017. Assessment of Montana Road Weather Information System, FHWA/MT-17-001/8229-001, Western Transportation Institute, Bozeman, MT. https://www.mdt.mt.gov/other/webdata/external/research/docs/research_proj/rwis_assess/final_report.pdf, last accessed June 6, 2023.

Federal Highway Administration (FHWA). Undated. "Maintenance Decision Support System (MDSS) Showcase" (website). https://ops.fhwa.dot.gov/weather/seminars/mdss_showcase/index.htm, last accessed June 6, 2023.

FHWA. n.d. "Organizing and Planning for Operations, What is TSMO?" (website). https://ops.fhwa.dot.gov/tsmo/#q1, last accessed June 6, 2023.

FHWA. 2015a. "Transportation Systems Management and Operations Benefit-Cost Analysis Compendium, Case Study 10.1 – Road Weather Pooled Fund Maintenance Decision Support System (MDSS) Implementation, Report." Report FHWA-HOP-14-032. Washington, DC. https://ops.fhwa.dot.gov/publications/fhwahop14032/ch10.htm, last accessed June 6, 2023.

FHWA. 2015b. "Transportation Engineering Approaches to Climate Resiliency (TEACR) Study" (website). https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/index.cfm, last accessed June 6, 2023.

FHWA. 2016a. "Hydraulic Engineering Circular No. 17, Highways in the River Environment Floodplains, Extreme Events, Risk, and Resilience." Publication No. FHWA-HIF-16-018. Washington, DC. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf, last accessed June 6, 2023.

FHWA. 2016b. *Comparison of Economic Analysis Methodologies and Assumptions: Dyke Bridge in Machias, Maine.* FHWA-HEP-17-022. https://web.archive.org/web/20170126133323/https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/dyke_bridge/fhwahep17022.pdf, last access June 6, 2023.

FHWA. 2017. *Synthesis of Approaches for Addressing Resilience in Project Development*. Report FHWA-HEP-17-082. Washington, DC: FHWA. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm, last accessed June 6, 2023.

FHWA. 2019a. *Weather Responsive Management Strategies (WRMS)—Minnesota DOT Case Study*. Report FHWA-HOP-19-080. Washington, DC: FHWA. https://ops.fhwa.dot.gov/publications/fhwahop19080/fhwahop19080.pdf, last accessed June 6, 2023.

FHWA. 2019b. "The Adaptation Decision-Making Assessment Process (ADAP)" (website). https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm, last accessed June 6, 2023.

FHWA. 2020a. *Crowdsourcing for Operations Case Study, Indiana Department of Transportation*. Report FHWA-HOP-20-053. Washington, DC: FHWA. https://www.fhwa.dot.gov/innovation/everydaycounts/edc_6/docs/crowdsourcing_case_study_indiana.pdf, last accessed June 6, 2023.

FHWA. 2020b. *Hydraulic Engineering Circular No. 25, Highways in the Coastal Environment* (3rd edition). Publication No. FHWA-HIF-19-059. Washington, DC: FHWA. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif19059.pdf, last accessed June 6, 2023.

FHWA. 2020c. *Weather-Responsive Management Strategies (WRMS) for Flood Management in Iowa, Missouri, and Nebraska*. Report FHWA-HOP-20-050. Washington, DC: FHWA. https://ops.fhwa.dot.gov/publications/fhwahop20050/index.htm, last accessed June 6, 2023.

FHWA. 2021. Weather-Responsive Management Strategies (WRMS) – Agency Tools to Manage Infrastructure Impacts during Flood Events. Report FHWA-HOP-21-013. Washington, DC: FHWA. https://ops.fhwa.dot.gov/publications/fhwahop21013/index.htm, last accessed June 6, 2023.

FHWA. 2022. "Road Weather Management Program" (website). https://ops.fhwa.dot.gov/weather/faq.htm#:~:text=A%20Road%20Weather%20Information%20System%20(RWIS)%20is%20comprised%20of%20Environmental,and%2For%20water%20level%20conditions, last accessed June 6, 2023.

FHWA. 2023a. "Bipartisan Infrastructure Law" (website). https://www.fhwa.dot.gov/bipartisan-infrastructure-law/, last accessed June 6, 2023.

FHWA. 2023b. "Transportation Engineering Approaches to Climate Resiliency (TEACR) Study" (website). https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/index.cfm, last accessed June 6, 2023.

Felio, G. 2015. "Vulnerability and Adaptation of Transportation Infrastructure to Climate Change." In TAC 2015: Getting You There Safely-2015 Conference and Exhibition of the Transportation Association of Canada. http://conf.tac-atc.ca/english/annualconference/tac2015/s13/felio.pdf, last accessed June 6, 2023.

Filosa, G., A. Plovnick, L. Stahl, R. Miller, and D. Pickrell. 2017. *Vulnerability Assessment and Adaptation Framework*, 3rd Edition. Report FHWA-HEP-18-020. Washington, DC: FHWA. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/index.cfm, last accessed June 6, 2023.

Fletcher, D., and D. Ekern. 2021. *Transportation System Resilience: Research Roadmap and White Papers*. NCHRP Report 975. Washington, DC: Transportation Research Board. Accessed at https://nap.nationalacademies.org/catalog/26160/transportation-system-resilience-research-roadmap-and-white-papers, last accessed June 6, 2023.

Gallagher, M., and C. Curd. 2021. Aftermarket Cameras in Winter Maintenance Vehicles, Project 1028783/CR17-03, Clear Roads Pooled Fund, Led by Minnesota DOT, June. https://clearroads.org/wp-content/uploads/dlm_uploads/FR_CR.17-03.pdf, last accessed June 6, 2023.

Gopalakrishna, D., J. Schroeder, A. Huff, A. Thomas, and A. Leibrand. 2013. *Planning for Systems Management & Operations as part of Climate Change Adaptation*. Report FHWA-HOP-13-030. Washington, DC: FHWA. https://ops.fhwa.dot.gov/publications/fhwahop13030/fhwahop13030.pdf, last accessed June 6, 2023.

Gopalakrishna, D., Martin, L., and Neuner, M. 2016. *2015 Road Weather Management Performance Measures*. Washington, DC: FHWA.

Harrison, F., W. Duke, J. Eldred. M. Pack, N. Ivanov, J. Crosset, and L. Chan. 2019. *Management and Use of Data for Transportation Performance Management: Guide for Practitioners,* NCHRP Report 931. Transportation Research Board, Washington DC. https://nap.nationalacademies.org/catalog/25462/management-and-use-of-data-for-transportation-performance-management-guide-for-practitioners, last accessed June 6, 2023.

Hassan, D., and H. McClintock. 2020. Virtual Road Weather Information Stations (RWIS) Enhancing Road Safety, Transportation Association of Canada. https://www.tac-atc.ca/en/conference/papers/virtual-road-weather-information-stations-rwis-enhancing-road-safety, last accessed June 6, 2023.

Houston TranStar. 2023. “Houston TranStar” (website). https://www.houstontranstar.org/, last accessed June 6, 2023.

Ibrahim-Watkins, R. Z. 2018. *Review of State of Practice—Evaluating the Performance of Transportation Infrastructures during Extreme Weather Events*. Presented at 97th Annual Meeting of the Transportation Research Board, Washington, DC.

ICF, Athey Creek Consultants, and Vaisala Inc. 2019. *Performance Measures in Snow and Ice Control Operations*. NCHRP Report 889. Washington, DC: Transportation Research Board. https://nap.nationalacademies.org/catalog/25410/performance-measures-in-snow-and-ice-control-operations, last accessed June 6, 2023.

Jacobs Engineering, Cambridge Systematics, and AEM Corporation. 2022. *Integrating Effective Transportation Performance, Risk, and Asset Management Practices*. NCHRP Report 985. Washington, DC: Transportation Research Board.

https://nap.nationalacademies.org/catalog/26326/integrating-effective-transportation-performance-risk-and-asset-management-practices, last accessed June 6, 2023.

Jiang, Q. D. Nian, Y. Guo, and J. Ma. 2021. *Evaluating Weather Responsive Freeway Management Strategies of Traveler Information Messages and Snowplow Pre-Positioning in a Connected Vehicle Environment*. Presented at the 100th Annual Meeting of the Transportation Research Board, Washington, DC. https://trid.trb.org/view/1759589, last accessed June 6, 2023.

Kim, E., and H. Mahmassani. 2021. *Integrating Connected Vehicle Data in Road Network Weather Management Systems: Snowplow Routing Application*. Presented at the 100th Annual Meeting of the Transportation Research Board, Washington, DC. https://trid.trb.org/view/1759157, last accessed June 6, 2023.

Knickerbocker, S., and A. Sassani. 2021. *Evaluation of Road Weather Messages on DMS Based on Roadside Pavement Sensors*. Report No. 2021-25. St. Paul, MN: Minnesota DOT. https://researchprojects.dot.state.mn.us/projectpages/pages/projectDetails.jsf?id=23870&type=CONTRACT&jftfdi=&jffi=projectDetails%3Fid%3D23870%26type%3DCONTRACT, last accessed June 6, 2023.

Lissade, H. 2012. "Flood Warning Alert Systems, Preliminary Investigation." Sacramento, CA: Caltrans Division of Research and Innovation.

Matherly, D., P. Bye, J. McDonald, W. Ankner, J. Mobley, K. Kim, E. Yamashita, P.Murray, Tuite, A. Pande, J. Renne, and B. Wolshon. 2021. *Resilience Primer for Transportation Executives*. NCHRP Report 976. Washington, DC: Transportation Research Board. https://nap.nationalacademies.org/catalog/26195/resilience-primer-for-transportation-executives, last accessed June 6, 2023.

McKeever, Haas, Weissmann, and Greer. 1998. "Life Cycle Cost-Benefit Model for Road Weather Information Systems," *Transportation Research Record 1627*, Washington, DC. https://journals.sagepub.com/home/TRR, last accessed June 6, 2023.

McNamara, M. L., H. Li, S. M. Remias, D. K. Horton, E. D. Cox, and D. M. Bullock. 2016. *Real-Time Probe Data Dashboards for Interstate Performance Monitoring During Winter Weather and Incidents*. Presented at the Transportation Research Board Annual Meeting, Washington, DC. Paper No. 16-0622. https://docs.lib.purdue.edu/civeng/20/, last accessed June 13, 2023.

Melnik, E. and B. Everitt (eds.). 2008. *Encyclopedia of Quantitative Risk Analysis and Assessment*, Volume 1. John Wiley & Sons.

Meyer, M., M. Flood, C. Dorney, J. Keller, G. McVoy, K. Leonard, and J. Smith. 2014. *Climate Change, Extreme Weather Events and the Highway System: Impacts and Adaptation Approaches.* NCHRP Report 750, Vol. 2. Washington, DC: Transportation Research Board. https://www.trb.org/Publications/Blurbs/169781.aspx, last accessed June 6, 2023.

Minnesota Department of Transportation (MnDOT). 2014. *Flash Flood Vulnerability and Adaptation Assessment Pilot Project*, St. Paul, MN. https://www.dot.state.mn.us/climate/pilotproject.html, last accessed June 6, 2023.

MnDOT 2022. *Extreme Flood Vulnerability Analysis*, St. Paul, MN. https://researchprojects.dot.state.mn.us/projectpages/pages/projectDetails.jsf?id=21038&type

=CONTRACT&jftfdi=&jffi=projectDetails?id=21038&type=CONTRACT, last accessed June 6, 2023.

National Oceanic and Atmospheric Administration (NOAA), Office of Water Prediction. Undated. "The National Water Model" (website). https://water.noaa.gov/about/nwm, last accessed June 6, 2023.

National Center for Atmospheric Research (NCAR). "Maintenance Decision Support System (MDSS®)" (website). https://ral.ucar.edu/solutions/products/maintenance-decision-support-system-mdss, last accessed June 6, 2023.

Neumeister, D., and D. Pape. 2016. *Prototype Road Weather Performance Management (RWPM) Tool Installation Instructions & User Manual.* Report FHWA-JPO-17-437. https://rosap.ntl.bts.gov/view/dot/32324, last accessed June 6, 2023.

Neumeister, D., and D. Pape. 2019. *Automated Vehicles and Adverse Weather,* Final Report. Report FHWA-JPO-19-755. https://rosap.ntl.bts.gov/view/dot/43772, last accessed June 6, 2023.

Nicolet-Monnier, M., and A. Gheorghe. 1996. *Quantitative Risk Assessment of Hazardous Materials Transport Systems, Rail, Road, Pipelines and Ship,* Topics in Safety, Risk, Reliability and Quality (TSRQ, volume 5). Springer Publishing. https://link.springer.com/book/10.1007/978-94-017-2821-8, last accessed June 6, 2023.

Oregon DOT. 2022. "US97 Road Weather Management" (website). https://gis.odot.state.or.us/tpt/projects/21501?city=Bend, last accessed June 6, 2023.

Ozcan, K., A. Sharma, S. Knickerbocker, J. Merickel, N. Hawkins, and M. Rizzo. 2020. "Road Weather Condition Estimation Using Fixed and Mobile Based Cameras." In: Arai, K., Kapoor, S. (eds) *Advances in Computer Vision. CVC 2019. Advances in Intelligent Systems and Computing,* vol 943. Springer, Cham. https://doi.org/10.1007/978-3-030-17795-9_14, last accessed June 6, 2023.

Park, S., V. Smith, and A. Hyde. 2021. "Practices for Integrated Flood Prediction and Response Systems," *NCHRP Synthesis 573*, Washington DC: The National Academies Press. https://doi.org/10.17226/26330 and as reported in Transportation Research Board. 2022. TR News #342 (November-December). https://onlinepubs.trb.org/onlinepubs/trnews/trnews342toc.pdf, last accessed June 6, 2023.

Pilli-Sihvola, E., and P. Leviakangas, and R. Hautala. 2012. "Better winter road weather information saves money, time, lives and the environment" in *Proceedings of the 19th Intelligent Transport Systems World Congress (ITS)*, Oct 22–26 2012. Vienna, Austria: SIRWEC. https://espace.curtin.edu.au/handle/20.500.11937/50594, last accessed June 6, 2023.

Pinellas County. 2020. *Sustainability and Resiliency Report*, December. https://pinellas.gov/sustainable-and-resiliency-report, last accessed June 6, 2023.

Pisano, P. 2019. "Are Your Roads Weather Savvy?" Publication No. FHWA-HRT-19-003, *Public Roads Magazine* 83, No. 1. https://highways.dot.gov/public-roads/spring-2019/are-your-roads-weather-savvy, last accessed June 6, 2023.

Prihodko, V., V. Vlasov, A. Tatashe, and N. Filippova. 2021. "Influence of Climatic Factors on the Implementation of Intelligent Transport System Technologies in the Regions of the Far North and the Arctic." *Transportation Research Procedia* 57: 495–501. https://www.sciencedirect.com/science/article/pii/S2352146521007055, last accessed June 6, 2023.

Sacramento Council of Governments (SACOG). 2020. Project-Level Adaptation Strategies Guidance Document, June. https://www.sacog.org/sites/main/files/file-attachments/sacog_project-level_climate_adaptation_strategies_final_report_3.pdf?1601491807, last accessed June 6, 2023.

San Diego Association of Governments (SANDAG). 2021. "Regional ITS Architecture, Caltrans RWIS" (website). San Diego, CA. https://its-arch.sandag.org/html/inv/el149.htm, last accessed June 6, 2023.

Sengupta, J., and S. Walker. 2020. "Road Weather Information Systems/Variable Message Sign Integration," *Transportation Association of Canada 2020 Conference and Exhibition* – The Journey to Safer Roads, 2020, 1 PDF file, 1.6 MB, 16p. https://www.tac-atc.ca/en/conference/papers/road-weather-information-systemsvariable-message-sign-integration, last accessed June 6, 2023.

Smart North Florida. n.d. "Building Resilience" (website). https://smartnorthflorida.com/projects/building-resiliency, last accessed June 6, 2023.

Sniffen, E., A. Bennett, S. Knight, K. Spidalieri, and M. Abkowitz. 2021. "Transportation Impacts in Managing Retreat from High-Risk Areas." Transportation Research Board webinar. https://onlinepubs.trb.org/onlinepubs/webinars/210304.pdf, last accessed June 6, 2023.

Stepanova, D., T. Sukuvaara, and V. Karsisto. 2020. "Intelligent Transport Systems – Road weather information and forecast system for vehicles," 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, pp. 1-5, doi: 10.1109/VTC2020-Spring48590.2020.9129368.

Szirocza D., D. Rohacs, and J. Rohacs. 2022. "Review of Using Small UAV Based Meteorological Measurements for Road Weather Management*," Progress in Aerospace Sciences* 134. https://www.sciencedirect.com/science/article/pii/S0376042122000513, last accessed June 6, 2023.

Tahir, Leviäkangas, and Katz. 2022. "Connected Vehicles: V2V and V2I Road Weather and Traffic Communication Using Cellular Technologies, Italian National Conference on Sensors. *Sensors 2022* 22, 1142. https://doi.org/10.3390/s22031142, last accessed June 6, 2023.

Transportation Research Board. 2019. *TRB Webinar: Road Weather and Flood Monitoring with the National Water Model*, Washington DC. https://www.trb.org/main/blurbs/178840.aspx#:~:text=National%20Water%20Model-,TRB%20Webinar%3A%20Road%20Weather%20and%20Flood%20Monitoring%20with%20the%20National%20Water%20Model,-TRB%20conducted%20a, last accessed June 6, 2023.

U.S. Department of Transportation (USDOT). n.d. "Justice40 Initiative." (website). https://www.transportation.gov/equity-Justice40, last accessed June 6, 2023.

USDOT. n.d. "Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation Program (PROTECT)" (website). Accessed at https://www.transportation.gov/rural/grant-toolkit/promoting-resilient-operations-transformative-efficient-and-cost-saving#:~:text=Under%20the%20Bipartisan%20Infrastructure%20Law,level%20rise%2C%20flooding%2C%20extreme%20weather, last accessed June 6, 2023.

U.S. Geographic Survey (USGS). n.d. "StreamStats" (website). https://www.usgs.gov/streamstats, last accessed June 6, 2023.

Veneziano, Shi, Ballard, Ye, and Fay. 2014. "A Benefit-Cost Analysis Toolkit for Road Weather Management Technologies." International Symposium of Climatic Effects on Pavement and Geotechnical Infrastructure 2013. https://ascelibrary.org/doi/10.1061/9780784413326.022, last accessed June 6, 2023.

West Riverside Council of Governments. "Adaptation and Resiliency Study" (website) n.d. Accessed at https://wrcog.us/DocumentCenter/View/7478/Western-Riverside-Adaptation-and-Resiliency-Strategy_Vulnerability-Assessment, last accessed June 6, 2023.

World Road Association (PIARC). n.d. "Weather Management, Technology, Data and Resources" (website). https://rno-its.piarc.org/en/network-control-traffic-management-integrated-strategies/weather-management, last accessed June 6, 2023.

U.S. Department of Transportation
Federal Highway Administration
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590

Office of Operations Web Site
https://ops.fhwa.dot.gov

September 2023
FHWA-HOP-23-047