GEORGIA DOT RESEARCH PROJECT 20-12

Final Report

INCORPORATING RESILIENCE CONSIDERATIONS IN TRANSPORTATION PLANNING, TSMO AND ASSET MANAGEMENT

Office of Performance-based Management and Research
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16. Abstract
This project integrates risk-based asset management procedures from the FHWA, AASHTO and the TRB with decision making under deep uncertainty (DMDU) concepts to develop climate vulnerability assessment, and planning and project evaluation capabilities for resilience building in transportation. The research framework includes: (1) understanding the climate hazards and threats to which an entity is exposed; (2) understanding their impacts; (3) determining vulnerability and risk and prioritizing needs for investment; and, (4) identifying, prioritizing and implementing actions to build resilience over time. The study develops multiple analytical, planning and prioritization tools and guidance to facilitate resilience building in transportation. It also provides resources for the continuing development of a range of resilience capabilities in the face of changing threats, and identifies performance measures to monitor and enhance infrastructure and organizational resilience, cost-effectively, in the short-term and long-term.

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GDOT Research Project No. 20-12

Final Report

TOWARDS THE IMPLEMENTATION OF A GEOTECHNICAL ASSET MANAGEMENT PROGRAM IN THE STATE OF GEORGIA

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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 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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 (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2000.

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY 10
2 INTRODUCTION 11
BACKGROUND 11
OBJECTIVES 13
OUTLINE 15
3 CONCEPTUAL FRAMEWORKS FOR BUILDING TRANSPORTATION RESILIENCE – EMERGING BEST PRACTICE 16
RISK-BASED FRAMEWORKS 16
UNCERTAINTY-BASED FRAMEWORKS 19
4 MULTI-HAZARDS EXPOSURE, VULNERABILITY, AND RISK ANALYSIS 21
DATA........ 21
ASSET EXPOSURE ESTIMATION 21
ASSET SENSITIVITY 24
ADAPTIVE CAPACITY 24
ASSET CRITICALITY 25
VULNERABILITY 26
RISK 26
ASSET PRIORITIZATION FOR RESILIENCE TREATMENT 27
SPECIFIC EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY 28
CLIMATE VULNERABILITY AND RISK ASSESSMENT – APPLICATIONS AND SIGNFICANCE 28
Cumulative and Hot Spot Analysis 29
Asset Exposure, Sensitivity, Criticality, Vulnerability and Risk Analysis 29
Asset Prioritization for Resilience Treatment 32
System Resilience Performance Monitoring and Management 35
5 CLIMATE ADAPTATION GUIDEBOOK FOR TRANSPORTATION PRACTITIONERS 38
OVERVIEW 38
DEVELOPMENT 38

APPLICATION 39
BROADER CONSIDERATIONS – ADAPTING INTERDEPENDENT SYSTEMS....40
6 PROJECT PRIORITIZATION INCORPORATING RESILIENCE CONSIDERATIONS 41
MULTIPLE CRITERIA METHODS (SHORTER-TERM APPROACH) 41
MODIFIED RESILIENCE TRIANGLE METHOD (LONGER-TERM APPROACH)....42
7 CLIMATE RESILIENCE METRICS....44
OVERVIEW: METRICS AND INDICATORS RECOMMENDED BY TRB, AASHTO AND FHWA....44
SYSTEM-LEVEL RESILIENCE METRICS 47
PORTFOLIO MEASURES FOR GENERAL RESILIENCE CAPABILITIES....48
RESILIENCE RATING TOOL AND SCORECARD 49
ADAPTIVE RESILIENCE CAPABILITY MATURITY MODEL (AR-CMM) 50
FLEXIBILITY/AGILITY SCORECARDS 50
BROADER CONSIDERATIONS - MEASURING RESILIENCE IN COMPLEX ADAPTIVE SYSTEMS....52
8 INCORPORATING RESILIENCE CONSIDERATIONS IN PLANNING, TAM AND TSMO 54
INCORPORATING FLEXIBILITY/AGILITY IN LONG-RANGE TRANSPORTATION PLANNING....54
Development 55
Recommendations for GDOT - integrating Resilience Considerations in LRTP 55
INCORPORATING RESILIENCE CONSIDERATIONS IN TAM 59
Uncertainty Requirements in TAMPs 59
State DOT Experiences Incorporating Uncertainty Considerations in TAMPs 60
TRANSPORTATION SYSTEMS MGMT. AND OPERATIONS (TSMO) PLAN DEVELOPMENT 62
Opportunities for TSMO Improvements to Build Resilience....62
Public transportation management....63
Travel demand management: 63
Event management:....63
Opportunities for Increased Resilience Building in TSMO 64
9 PLANNING AND PROJECT EVALUATION UNDER DEEP UNCERTAINTY: A PROCESS GUIDE 67

THE TOP-DOWN APPROACH....................67
THE BOTTOM-UP APPROACH 68
THE PROJECT-LEVEL APPROACH.................... 68
Case Study: The Talmadge Memorial Bridge 69
CLIMATE HAZARDS AND SENSOR MONITORING SOLUTIONS....................70
10 CONCLUSION....................73
11 ACKNOWLEDGEMENTS 74
12 REFERENCES....................75

TABLE OF FIGURES

Figure 1. Graph Frequency and Costs of Billion-Dollar Climate Events in the United States (NOAA) 11

Figure 2. Diagram Study Framework - Vulnerability/Risk Assessment and Adaptive Resilience Framework 15

Figure 3. Diagram TRB Committee on Resilience Metrics Framework for Assessing Climate Hazard Risks and Investment for Resilience Enhancement (TRB 2021 | Reproduced) 17

Figure 4. Diagram AASHTO FEAR-NAHT Framework for Vulnerability Assessment and Resilience Enhancement (AASHTO 2021 | Reproduced) 18

Figure 5. Diagram. FHWA Vulnerability Assessment and Adaptation Framework (FHWA 2017 | Reproduced) 19

Figure 6. Table. Progressive Levels of Uncertainty from Complete Determinism to Total Ignorance (Marchau et al. 2019) 20

Figure 7. Matrix: Asset Prioritization using Dynamic Vulnerability and Risk 27

Figure 8. Map. Cumulative Thunderstorm Events (1960-2020) (MHEVRA Tool/SHELDUS) 30

Figure 9. Map: Thunderstorm Hot Spots (1990-2020) (MHEVRA Tool/SHELDUS) 31

Figure 10. Maps. Pavements - General Exposure, General Sensitivity, Criticality, General Vulnerability and General Risk (MHEVRA Tool/SHELDUS) 32

Figure 11. Map: Pavements - Prioritization by Vulnerability and Criticality - Spatial State and District Level Views (MHEVRA Tool/SHELDUS) 34

Figure 12. Graph: Pavements - Prioritization by Vulnerability and Criticality - District-Level View (MHEVRA Tool/SHELDUS) 35

Figure 13. Chart: Pavement Vulnerability Distributions for the State of Georgia and for GDOT's Seven Districts (MHEVRA Tool/SHELDUS) 36

Figure 14. Chart: Bridge Risk Distributions for the State of Georgia and for GDOT's Seven Districts (MHEVRA Tool/SHELDUS) 36

Figure 15. Map: Specific Vulnerability of Bridges to Scour caused by Inland and Coastal Flooding (MHEVRA Tool/SHELDUS) 36

Figure 16. Matrix: Sequence of Steps for Navigating the District-Level Adaptation Planning Section of Guidebook (Tennakoon et al. 2023) 39

Figure 17. Graph: MRT Output - Resilience Losses and Benefits for Various Case Study Scenarios (Singh et al. 2023) 43

Figure 18. Document: Access Information for Resilience & Scorecard 49

Figure 19. Document: Access Information for Adaptive Resilience Capability Maturity Model 50

Figure 20. Scorecard: Example Application of Flexibility & Agility Scorecards (Garrett 2023, Garrett et al. 2023) 51

Figure 21. Matrix: Flexibility and Agility Dimensions mapped to the Steps in the Long-Range Transportation Planning Process (Garrett 2023, Garrett et al. 2023) 55

Figure 22. Diagram: Informing Relationship Among the Three Components of Uncertainty Planning (Cuadra 2023, Cuadra et al. 2023) 67

Figure 23. Diagram: Lifecycle Costs of Modeled Case-Study Alternatives with Recommendations (Cuadra 2023, Cuadra et al. 2023) 69

TABLE OF TABLES

Table 1. Climate Hazard Exposure - Score Categories based on Hot Spot Analysis Results 22

Table 2. Climate Hazard Exposure - Weights from Hazard-Asset Pairs with Failure Mechanisms 23

Table 3. Estimation of General Exposure for Pavements 24

Table 4. Factors for Estimating Criticality Score at GDOT* 26

Table 5. Flexible Project Prioritization Metrics Including Resilience and Equity Considerations 42

Table 6. System-Level Resilience Metrics using the MHEVRA and other Tools........ 48

Table 7. Portfolio of Resilience Metrics Organized by Common Resilience Capabilities... 49

Table 8. Areas and Opportunities for Resilience Considerations in TAMPs........ 61

Table 9. Strategies to Build Resilience and Mitigate Threats Using TSMO 63

Table 10. Areas and Opportunities to Incorporate Resilience Considerations in TSMO Planning 64

Final Report

INCORPORATING RESILIENCE CONSIDERATIONS IN TRANSPORTATION PLANNING, TSMO AND ASSET MANAGEMENT
RP 20-12

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August 22, 2023

1 EXECUTIVE SUMMARY

Over the past four decades, transportation system performance has been increasingly influenced by climate, cybersecurity, public health and technology disruptions, occurring amid more traditional acute shocks (such as fuel shortages), and chronic stressors (such as traffic congestion). In the United States, data show that billion-dollar event frequency, annual cost, and 5-year cost averages have all increased from 1980 to 2021. At the same time, public and private agencies, communities and other entities have begun formal programs to build resilience to these disruptions. This report summarizes the creation of capabilities for climate resilience building at the Georgia Department of Transportation (GDOT) through a 3-year research and development study: *Incorporating Resilience Considerations in Transportation Planning, TSMO and Asset Management* (RP 20-12).

While there are several definitions of resilience, superior definitions will enable an agency to **develop capabilities** for reducing organizational and infrastructure system vulnerabilities to known threats, managing less known and unknown threats, and, recognizing and seizing appropriate opportunities to continue to preserve and enhance system performance. In this project, **resilience is defined as the ability to anticipate, prepare for, adapt to changing conditions and withstand, respond, recover rapidly from disruptions; degrade safely under unanticipated conditions, and, proactively manage the factors that perpetrate or exacerbate these disruptions**. For resilience to be sustained, performance disruptions and their exacerbating factors must be managed.

The research framework used in this study draws from three authoritative frameworks for risk-based vulnerability assessment and resilience building offered by the Federal Highway Administration, the American Association of State Transportation and Highway Officials, and the Transportation Research Board of the National Academies, respectively. Additionally, it draws from a body of knowledge developed by the Society for Decision Making Under Deep Uncertainty (DMDU) to create decision-support tools that facilitate resilience building to deeply uncertain events. The research framework includes the following: (1) understanding the climate hazards and threats to which an entity is exposed; (2) understanding their impacts; (3) determining vulnerability/risk and prioritizing needs for investment; and, (4) identifying and implementing actions to build resilience. It also involves the continuing development of a range of resilience capabilities in the face of changing threats, and, applications of scenario, robustness, dynamic and adaptive approaches to build resilience to threats that are difficult or impossible to anticipate.

Agencies may implement this holistic approach to identify the most critical climate hazards to which they are exposed, update this information periodically, work with stakeholders to prioritize needs, identify and prioritize resilience improvement strategies and monitoring plans, leverage federal and state funding to implement these strategies, and, continue to build a range of resilience capabilities in order to strengthen resilience in the face of changing threats to maintain a highly-performing transportation system.

2 INTRODUCTION

BACKGROUND

Transportation systems are exposed to a wide range of disruptions that can affect system performance, sometimes significantly. Over the past four decades, several transportation and other systems have increasingly been exposed to disruptions from the changing climate. Extreme heat and rainfall, increased average temperatures and rainfall, flooding, sea level rise, intensifying wind speeds and a range of other climatic factors have become more important in the performance of transportation and other systems. Data from the National Centers for Environmental Information (NCEI) in the National Oceanic and Atmospheric Administration (NOAA) show that the frequency, annual cost, and five-year cost average for billion-dollar disasters in the U.S. have all increased over the period from 1980 through 2021 (**Figure 1**).

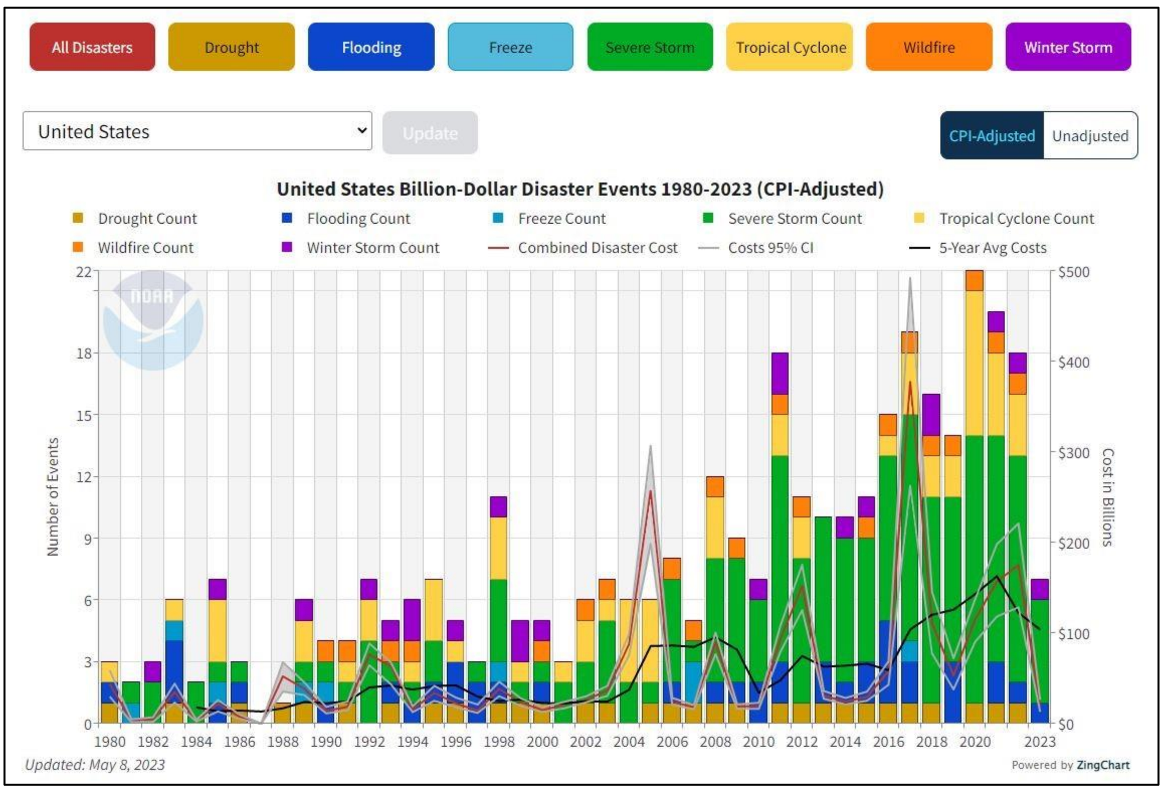


Figure 1. Graph Frequency and Costs of Billion-Dollar Climate Events in the United States (NOAA)

How do these changing climate hazards, individually and collectively, affect transportation system performance and the quality of life (QOL) of the users who depend on these systems? How should transportation agencies adapt to these changes in order to preserve and continue to enhance system performance and community QOL? This report presents a summary of a three-year research and development effort conducted to help GDOT develop the capabilities to build resilience to known and unknown climate threats.

While resilience has several definitions, superior definitions will equip a transportation agency to build **a range of resilience capabilities to address both known and unknown threats** on an ongoing basis - in order to continue to preserve and enhance transportation system performance. These efforts will include but not be limited to the reduction of organizational and system vulnerability. To this end, the outcomes-based definition of resilience developed by AASHTO (the American Association of State Highway and Transportation Officials) at the *2017 Transportation Hazards and Security Summit* is a practical performance-based definition for incorporating resilience considerations in existing performance management processes: **The ability of a system to provide an acceptable level of service and functionality in the face of major shocks and disruptions to normal operations** (AASHTO 2017). The study adopted this outcomes-based definition of resilience.

The study also adopted the following broader lifecycle definition of resilience to guide the research: **the ability to anticipate, prepare for, adapt to changing conditions and withstand, respond, recover rapidly from disruptions; degrade safely under unanticipated conditions, and, proactively manage the factors that perpetrate or exacerbate these disruptions** (NRC 2012, Allenby & Fink 2005). For resilience to be sustained in the long run, **performance disruptions as well as their fundamental causes must be managed**.

The study draws from three authoritative vulnerability assessment and resilience-building frameworks offered by the Federal Highway Administration (FHWA 2017), the American Association of State Highway and Transportation Officials (AASHTO 2021) and the Transportation Research Board of the National Academies (TRB 2021) to support the development of risk-based approaches to climate vulnerability and risk assessment.[1] The study also draws from the Decision Making Under Deep Uncertainty (DMDU) body of knowledge (Marchau et al. 2019) to support the development of capabilities to address very extreme or unknown threats, e.g., COVID-19, offering an expanded conceptual framework that addresses both known and unknown climate threats - that is, threats that can be anticipated and quantified, and those that cannot.

[1] While the latter two reports were finally published by the National Academies, their primary sponsors were AASHTO and the Transportation Research Board's Committee on Transportation Resilience Metrics, respectively. This report uses AASHTO and TRB to refer to these reports to emphasize their primary sources.

OBJECTIVES

The overarching objective of this study is to equip GDOT to create an increasingly climate-resilient transportation system, in an efficient manner. The study thus develops decision-support tools, identifies and assembles data with applications to the organization, its institutions and the physical transportation system; and, makes recommendations to enhance the resilience of agency plans. We develop a multi-hazards exposure, vulnerability and risk assessment methodology and tool (i.e., **the MHEVRA Tool**) (Yang & Amekudzi-Kennedy 2023) using data from the Spatial Hazards Events and Losses Database for the United States (**SHELDUS**) - a long-term database beginning in 1960 with data collection at the county scale on climate hazards that cause billion-dollar disasters (CEMHS 2023). The approach conducts a GIS-based hot spot analysis to identify and prioritize the most significant hot spots for climate hazard exposure. Asset-failure mechanisms, related asset condition data, asset criticality data and adaptive capacity data are all used in evaluating asset vulnerability to climate hazards, as well as asset risk. These outputs are then used in prioritizing assets for resilience improvement.

A **climate adaptation guide** was developed to support transportation practitioners in identifying superior resilience-building alternatives in conjunction with internal and external stakeholders (Tennakoon 2023, Tennakoon et al. 2023). A **treatise addressing interdependencies in adaptation** was also developed to highlight several nuances of adaptation at the system, organization and project levels (Cuadra et al. *In Press*). To support project prioritization, a set of **flexible project prioritization metrics**, including resilience and social equity considerations, was developed to assist the agency in tailoring prioritization metrics most appropriately to various funding sources - in order to maximize the chance of securing funds (Garrett et al. 2023a). A **modified resilience triangles methodology** was also developed to assess the long-term benefits of alternative adaptive resilience strategies with example applications (Singh 2021, Singh et al. 2023).

Monitoring climate threats and asset condition may be more appropriate for certain portions of the system or certain assets that are not in the high-vulnerability/high-criticality category. **Recommendations are offered from a sensor pilot** demonstrating the value of monitoring for assets or portions of the system that either fall within the categories of high-vulnerability/low-criticality or low-vulnerability/high-criticality and have forming hot spots or other activity that warrants closer observation. The sensor pilot demonstrates the instrumentation of a bridge for scour, sea level rise, tide activity, and bridge pier condition monitoring to explore the most cost-effective hardware and software solutions for such monitoring and the use of data in predicting future condition and prioritizing bridge elements for resilience improvement. Such monitoring activity can facilitate identification for long-term monitoring the most appropriate asset-hazard combinations in the high-vulnerability/low-criticality or low-vulnerability/high-criticality categories.

Beyond capabilities for determining and prioritizing vulnerable assets and portions of the system for resilience improvement, the study also develops tools to assist the agency in building organizational resilience, in particular adaptive capacity, to address all kinds of threats: known, lesser known and unknown. The study develops an **Adaptive Resilience Capability Maturity Model** (AR-CMM) (Singh 2021, Singh et al. 2022), **Flexibility and Agility Scorecards** (Garrett 2023), and a **Resilience Rating Tool and Scorecard** patterned after the World Bank's Resilience Rating System (2021) – all of which enable an agency to self-assess and continue to develop its adaptive capacity, in order to reduce its vulnerability to both known and unknown climate threats. The study also assembles a **portfolio of resilience metrics** from the literature to help an agency build its preparedness, robustness, recovery and capacity-to-reorganize capabilities (Williams et al. *IRG Working Paper Series*).

In addition, the study develops the **authentic equity planning framework** with recommendations for incorporating social equity, critical to resilience building, in long-range transportation planning (Garrett et al. 2023b). Furthermore, the study develops **recommendations for incorporating flexibility and agility**, precursors of adaptive capacity, into long-range transportation plans (Garrett 2023), and **resilience considerations in Transportation Systems Management and Operations (TSMO) and Transportation Asset Management (TAM)**. Finally, the study also develops a **Process Guide for Uncertainty Planning** with a demonstration on how to address deep uncertainty when reviewing alternatives using the Talmadge Memorial Bridge replacement as a case study (Cuadra 2023).

Collectively, these analytical, planning, and monitoring tools and data equip the agency to stay abreast with the climate hazards to which it is exposed, to understand better how this exposure is changing, to prioritize its assets and system for cost-effective resilience improvement, to monitor portions of the system that are not in the high-vulnerability/high-criticality category but may move to this category in the future; and, to continue to develop adaptive capacity at the organizational level and infuse it in agency policy, design standards, plans, programs and projects.

Figure 2 illustrates the **vulnerability assessment and adaptive resilience building approach** for known and unknown climate threats developed and used in this study (Amekudzi-Kennedy et al. *In Press*). This research framework draws from the three authoritative frameworks from the FHWA, AASHTO and TRB, introduced earlier. These frameworks are discussed in more detail in the next section of the report.

OUTLINE

In the sections below, we present the key resilience frameworks that informed this study, and discuss in detail each of the decision-support resources developed for GDOT's resiliency toolkit with examples of how they may be applied and the value they can generate for the agency's resilience-building efforts.

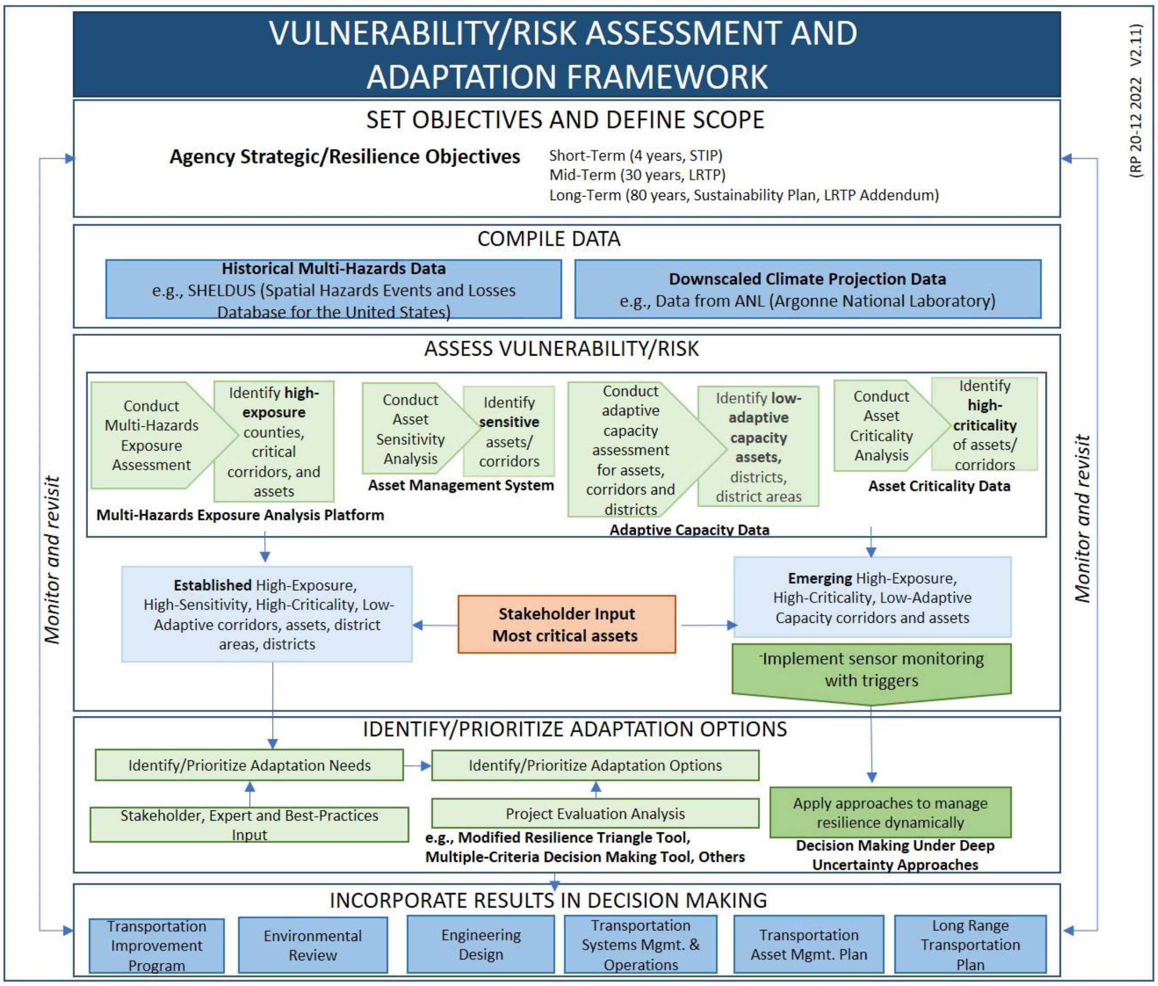


Figure 2. Diagram Study Framework - Vulnerability/Risk Assessment and Adaptive Resilience Framework (Amekudzi-Kennedy et al. In Press)

3 CONCEPTUAL FRAMEWORKS FOR BUILDING TRANSPORTATION RESILIENCE – EMERGING BEST PRACTICE

A comprehensive climate vulnerability assessment and resilience building approach will address both known threats and unknown threats or very extreme events. Addressing known threats is usually done applying **risk-based approaches**. These approaches result in the building of **specific resilience** (that is, resilience to specific threats). Addressing unknown threats is done using **uncertainty-based approaches** or deep uncertainty-based approaches. These approaches result in the building of **general resilience** (that is, resilience to threats in general). Because communities are faced with both known and unknown threats, building resilience only to known threats is ultimately an insufficient approach to resilience building.

RISK-BASED FRAMEWORKS

Three authoritative transportation organizations have published conceptual frameworks for climate vulnerability assessment and resilience building in the past few years: the Federal Highway Administration (2017), the American Association of State Highway and Transportation Officials (2021), and the Transportation Research Board's Committee on Resilience Metrics (2021). The latter two of these reports were published by the National Academies of Sciences, Engineering and Medicine. These frameworks reveal the best practices in the U.S. for climate vulnerability assessment and resilience building for transportation systems. The approaches are risk-based in the sense that they focus on identifying specific hazards and characterizing and quantifying their uncertainties using probabilistic methods (that is, they apply probabilistic risk assessment). They also focus on understanding the sensitivity of the assets, system (and sometimes organization) to these hazards; identifying the impacts of these hazards on valuable community assets (e.g., human life and quality of life (QOL), infrastructure and businesses), prioritizing the system/assets for resilience improvement, and identifying and prioritizing resilience improvement strategies to build resilience to the hazards of concern in the most vulnerable assets or portions of the system.

Common and core elements of the three **risk-based frameworks** suggest that a climate vulnerability assessment of a transportation system will do the following:

(1) Support identification of climate hazards to which the system under study is exposed;
(2) Shed light on how these assets are likely to affect the system and the consequences of these hazards on the infrastructure, human life and QOL, and, the economy of the system users;

(3) Facilitate prioritization of the assets or system elements for resilience improvement; and,
(4) Support identification and prioritization of appropriate resilience strategies to futureproof the system, in an efficient manner.

Figures 3, 4, and **5** depict the TRB, AASHTO and FHWA approaches, respectively – all risk-based approaches – meaning they identify the hazards, and are able to characterize and quantify their uncertainties (probabilistically), with confidence.

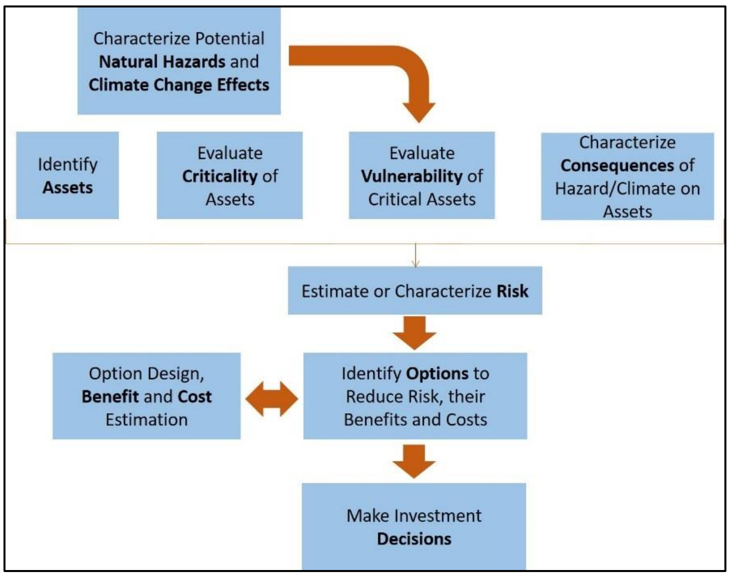


Figure 3. Diagram TRB Committee on Resilience Metrics Framework for Assessing Climate Hazard Risks and Investment for Resilience Enhancement (TRB 2021 | Reproduced)

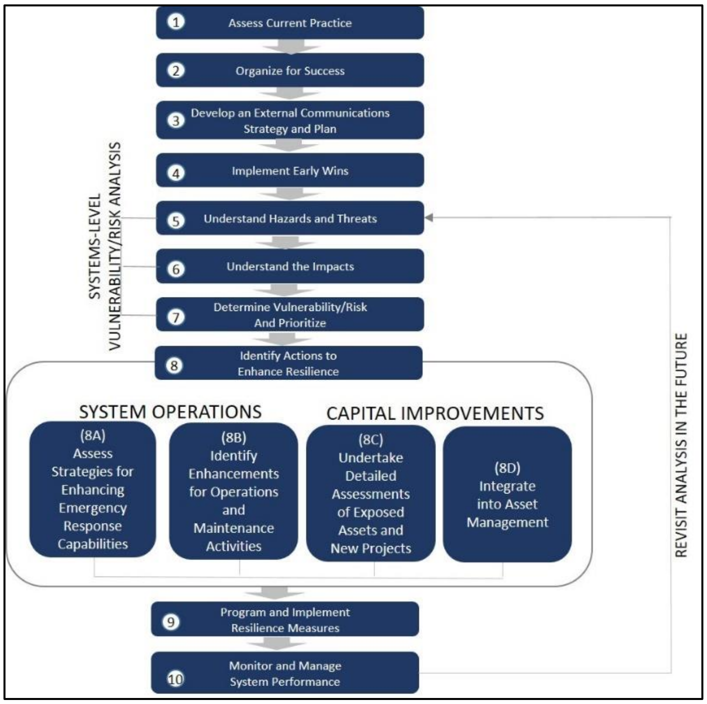


Figure 4. Diagram AASHTO FEAR-NAHT Framework for Vulnerability Assessment and Resilience Enhancement (AASHTO 2021 | Reproduced)

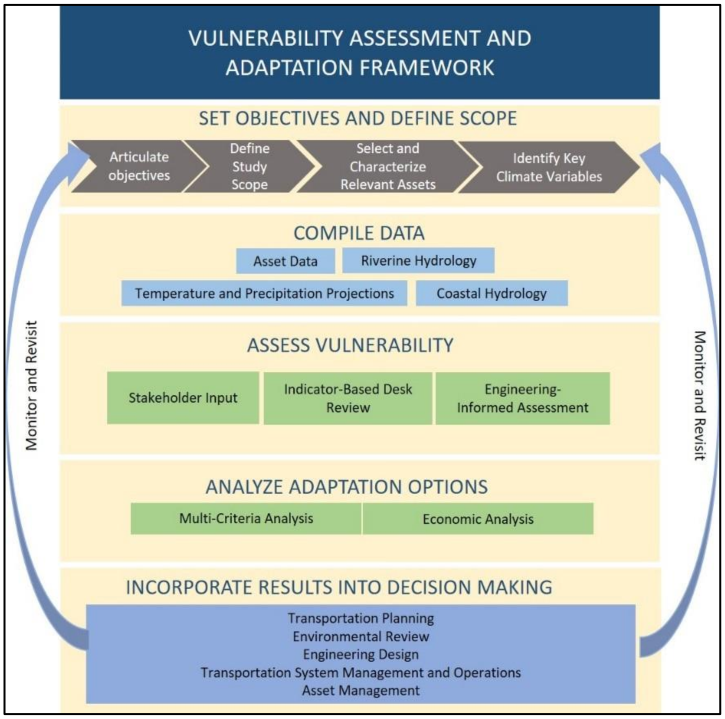


Figure 5. Diagram. FHWA Vulnerability Assessment and Adaptation Framework (FHWA 2017 | Reproduced)

UNCERTAINTY-BASED FRAMEWORKS

What happens when we cannot quantitatively characterize the uncertainty surrounding a threat, confidently, as in the case of COVID-19 - for example? In such cases, risk-based frameworks do not work. We must fall on **uncertainty-based frameworks**. **Figure 6** depicts different levels of uncertainty - from complete knowledge to total ignorance. Risk-based frameworks are useful for characterizing level 1 and level 2 uncertainties. **When we move to level 3 and level 4 uncertainties, we must make use of uncertainty and deep uncertainty frameworks, such as scenario-based frameworks, robustness, dynamic and adaptive frameworks** (Marchau et al. 2019).

An example of a level 1 uncertainty is traffic congestion in most metropolitan areas during the peak periods – it is certain that there will be congestion, and analysts are able to estimate the levels of congestion with high levels of confidence, using sensitivity analysis. An example of a level 2 uncertainty is flood risk, when past flood occurrences were a good predictor of future flooding and could be modeled probabilistically using a return period (pre-anthropocentric climate change). The return period is no longer stationary in several regions. The future of autonomous vehicles could be viewed as a level 3 type of uncertainty – one of five alternatives from full control to full automation may materialize. An example of level 4a uncertainty is our global climate future: there are many plausible futures depending on our carbon emission levels, with transportation being a primary sector for carbon emissions in the U.S. and around the world. Level 4b uncertainties are unknown to us and seldom planned for until they occur; for example, very few if any organizations planned for the COVID-19 Pandemic.

	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future	Alternate futures (with probabilities)	A few plausible futures	Many plausible futures	Unknown future	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 6. Table. Progressive Levels of Uncertainty from Complete Determinism to Total Ignorance (Marchau et al. 2019)

When we cannot quantitatively characterize the uncertainty around a threat with high levels of confidence (i.e., levels 3 and 4), we must fall on **decision making under uncertainty** (e.g., scenario-based methods) or **decision making under deep uncertainty** (DMDU) approaches (e.g., robustness, dynamic and adaptive approaches) (Marchau et al. 2019). In a decision-making context, deep uncertainty describes situations where various parties facing a decision do not know or cannot agree on: (1) how a system works; (2) how likely various possible future states of the world are, and, (3) how important the various outcomes of interest are (Lempert et al. 2003). In a data/analytical context, deep uncertainty is a situation in which analysts do not know or cannot agree on: (1) models that relate key forces that shape the future; (2) probability distributions of key variables or parameters in these models, and/or, (3) the value of alternate outcomes (Hallegatte et al. 2012). Several aspects of transportation systems fall into the deep uncertainty category.

In those cases where uncertain threats cannot be modeled with confidence or when threats are unknown, there is value in developing adaptively – developing flexibility, agility and adaptiveness to enable enhanced responsiveness in real time when very extreme or unknown events occur. This enhanced level of adaptiveness can also be developed by applying scenario, dynamic, adaptive and robustness planning approaches (see for example Marchau et al. 2019, Lempert et al. 2021, Popp 2021, Amekudzi-Kennedy et al. *In Press*, and, Cuadra 2023). Thus, an agency that applies both risk-based and uncertainty-based approaches, as depicted in **Figure 1**, is preparing its system and organization better to handle both known and unknown threats - including very extreme events. In the sections below, we discuss the analytical and planning methodologies and decision-support tools developed in this study to handle **both known and unknown threats** in order to build both specific and general resilience in transportation systems.

4 MULTI-HAZARDS EXPOSURE, VULNERABILITY, AND RISK ANALYSIS

The Multi-Hazards Exposure, Vulnerability and Risk Analysis Tool (also known as the **MHEVRA Tool**) was developed in this study to conduct climate exposure, vulnerability and risk analysis on pavements, bridges and culverts. Design and programming details are available in the **MHEVRA Tool Manual** (Yang et al. 2023). The MHEVRA Tool's capabilities may be extended to address other transportation asset categories as desired in the future.

DATA

The MEHVRA approach makes use of the Spatial Hazards Events and Losses Database for the United States (SHELDUS), a long-term database with data collection beginning in 1960, at the county level, for a range of climate hazards that have caused billion-dollar disasters. These hazards include thunderstorms, hurricanes, wildfires, floods, tornadoes, heavy rainfall, extreme heat, drought, landslides and others. Developed by the Hazards and Vulnerability Institute at the University of South Carolina with the support of the National Science Foundation, the dataset has been maintained since 2018 by the Center for Emergency Management and Homeland Security (CEMHS) at the Arizona State University. The SHELDUS data is updated on a yearly basis and is available for a subscription fee (CEMHS 2023).

ASSET EXPOSURE ESTIMATION

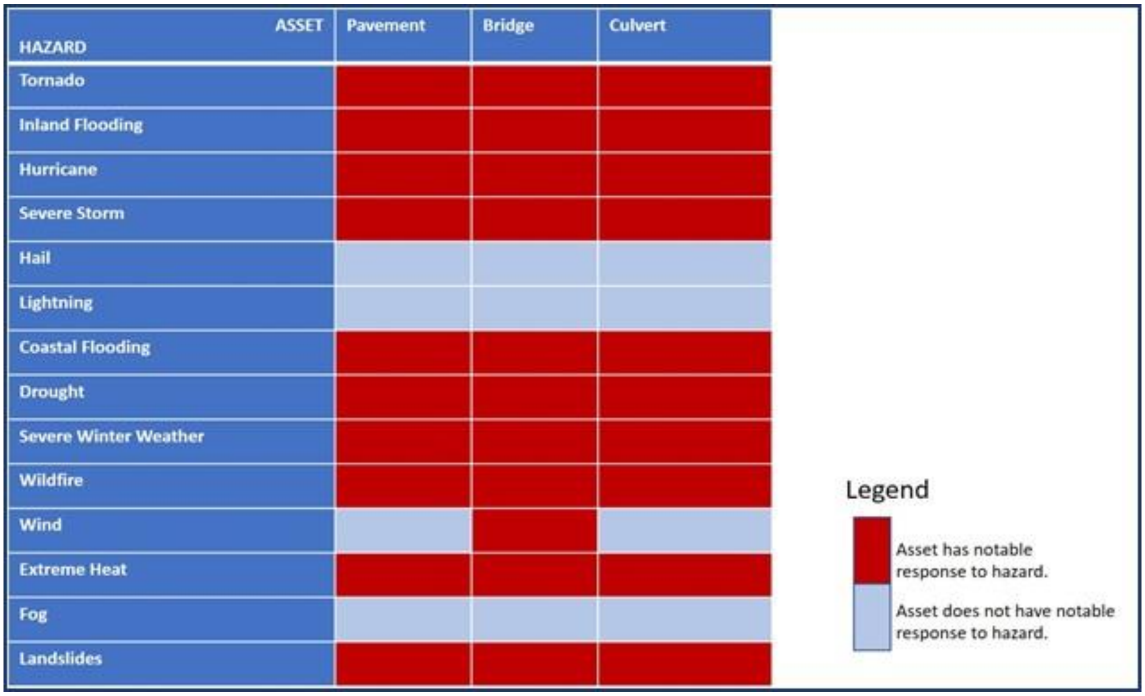
A prerequisite for vulnerability, exposure refers to whether an asset or system is located in an area experiencing the direct effects of climate vulnerability and extreme weather events (FHWA 2017). Exposure is the presence of infrastructure in places or settings where it could be affected by hazards or threats - for example, a road in a flood plain (AASHTO 2021). A Multiple Criteria Decision Making (MCDM) methodology was used to develop a multi-hazards exposure index for pavements, bridges and culverts. The exposure index is amalgamated from hazard scores resulting from GIS-based hot spot analysis as well as weights capturing the specific hazards that have the potential to reduce asset performance, that is, the hazard-asset pairs that have known failure mechanisms.

Table 1 shows the different hot spots resulting from the hot spot analysis, and **Table 2** shows the hazard-asset pairs that have failure mechanisms and are used in assigning weights in the MCDM analysis. By default, equal weights are assigned to all the hazards that can result in reduced performance of a particular asset (that is, pavement, bridge or culvert). The weights may be modified based on the knowledge of local practitioners of the relative importance of specific hazards, as well as their interactions, to asset and system performance. **Equation 1** shows how the multi-hazards exposure score for a pavement is calculated. The same approach is applied to calculate multi-hazard exposure scores for bridges and culverts.

Table 1. Climate Hazard Exposure - Score Categories based on Hot Spot Analysis Results

Hot Spot	Definition	Score	Normalized Score
Intensifying (I)	A location that has been a statistically significant hot spot for more than 90% time steps, including the final time step. In addition, the intensity of clustering of high counts in each time step is increasing.	8	1.00
Persistent (P)	A location that has been a statistically significant hot spot for more than 90%, with no discernible trend indicating an increase or decrease in the intensity of clustering over time.	7	0.875
Diminishing (D)	A location that has been a statistically significant hot spot for more than 90% time steps. In addition, the intensity of clustering of high counts in each time step is decreasing, or the most recent time step is not hot.	6	0.75
New (N)	A location that is a statistically significant hot spot only for the last time steps of the time series.	5	0.675
Consecutive (C)	A location with a single uninterrupted run of statistically significant hot spot bins in the final time-step intervals. The location has never been a statistically significant hot spot prior to the final hot spot run and less than 90% of time steps are statistically significant hot spots.	4	0.5
Sporadic (S)	A location that is an on-again then off-again hot spot. Less than 90% time steps have been statistically significant hot spots.	3	0.375
Oscillating (Os)	A statistically significant hot spot for the final time-step that has a history of also being a statistically significant cold spot during a prior time step. Less than 90% of the time-step intervals have been statistically significant hot spots.	2	0.25
Historical (H)	The most recent time period is not hot, but at least 90 percent of the time-step intervals have been statistically significant hot spots.	1	0.125
Others (Ot)	All cold spots and other non-significant hot-spot categories.	0	0

Table 2. Climate Hazard Exposure - Weights from Hazard-Asset Pairs with Failure Mechanisms



$$General\ Exposure\ Score\ for\ Pavements\ (E_p) = \sum_{i=1}^{n} W_i \times e_{ic} \ldots \quad \textbf{Equation 1}$$

where E_P = General Exposure Score for Pavements (capturing pavement exposure to all climate hazards that affect pavement performance, and factoring in the relative importance of those hazards (individually and combinatively) to pavement performance)

W_i = Weight of particular Hazard i

S_i = Normalized Hot Spot Score for a particular Hazard i (based on the hot spot category identified in *Table 2*; the hot spot category is identified based on the hot spot analysis for the county where the infrastructure asset is found.)

Table 3 below illustrates the estimation of the general exposure of pavements to climate hazards in three different counties. This exposure has a dynamic element introduced by the results of the hot spot analysis and may be referred to as dynamic pavement exposure. The data show that County 2 has the highest exposure to climate hazards in general, followed by County 3, and then followed by County 1.

Table 3. Estimation of General Exposure for Pavements

		E_C = Normalized Exposure Score for Pavement in County C for Hazard i, based on the host-spot category identified from Table 1		
County Hazard	Weight	County 1	County 2	County 3
Tornadoes	0.1	1.00	1.00	0.86
Inland Flooding	0.1	0.00	1.00	0.86
Hurricane Wind	0.1	0.43	1.00	0.86
Severe Storm	0.1	0.29	1.00	0.86
Coastal Flooding	0.1	0.00	1.00	0.86
Drought	0.1	0.00	1.00	0.14
Severe Winter Weather	0.1	0.57	1.00	0.14
Wildfire	0.1	0.57	1.00	0.14
Extreme Heat	0.1	0.86	1.00	0.14
Landslide	0.1	0.43	1.00	0.14
Pavement Exposure Score		**0.37**	**1.00**	**0.50**

ASSET SENSITIVITY

Asset sensitivity refers to whether the asset will be damaged or disrupted by the stressor (TRB 2021, Gye 2015). In this study, we estimated general sensitivity for pavements, bridges and culverts using network-level condition measures: Pavement Condition Index (PCI), Bridge Sufficiency Rating, and Culvert Condition Index. The inverse of these values was applied to capture the general sensitivity of these assets to the particular hazards (**Table 2**) to which they were exposed. Data for the PCI were obtained from the Georgia Department of Transportation and data for the Bridge Sufficiency Rating and Culvert Condition Index were pulled from the National Bridge Inventory.

ADAPTIVE CAPACITY

Adaptive capacity refers to the ability of a system to adjust, repair and respond to damage or disruption (TRB 2021, Gye 2015). Adaptive capacity may be measured in various ways. In this study we proposed the use of one or more capability maturity models or tools measuring the agency's (or transportation district's) capability for resilience building, including vulnerability reduction. The Resilience Rating Tool and Scorecard, patterned after the World Bank's Resilience Rating System measures the agency's capabilities to conduct vulnerability assessment and reduce vulnerabilities, as well as take broader measures to strengthen resilience, economic advancement and sustainability (World Bank 2021); the Adaptive Resilience Capability Maturity Model (AR-CMM) measures the agency's ability to adapt to changing conditions and build resilience (Singh 2021, Singh et al. 2022); and Flexibility/Agility Scorecards help the agency to enhance flexibility and agility within the long-range transportation plan, both of which are precursors to adaptive capacity (Garrett 2023).

Assuming that all transportation districts were at the beginning stages of building adaptive capacity, the Research Team ascribed a unit score to all seven GDOT districts for this measure. From a transportation systems management and operations (TSMO) and emergency operations perspective, route redundancy is a measure of adaptive capacity. From a transportation asset management (TAM) perspective, building back better is a measure of adaptive capacity to strengthen resilience to identified vulnerabilities. Armed with the knowledge that **what gets measured gets managed**, agencies may decide on and prioritize various measures of adaptive capacity that best address their climate vulnerabilities and include these in their climate vulnerability assessment and performance management procedures.

ASSET CRITICALITY

Criticality refers to the importance or value of infrastructure asset, in terms of the cost to users, owners and society from a loss in function (TRB 2021). A critical asset is an asset that is so important to a study area that its removal would result in significant losses (FHWA 2011). The vulnerability assessment approach makes use of the GDOT State Route Prioritization Criteria shown in **Table 4** below (and weighted at 80%) combined with the social vulnerability index (weighted at 20%) to start to incorporate social equity considerations. Developed by the Centers for Disease Control and Prevention (CDC), and the Agency for Toxic Substances and Disease Registry (ATSDR), the CDC/ATSDR social vulnerability index (SVI) refers to the potential negative effects on communities caused by external stresses on human health – including natural or human-caused disasters, or disease outbreaks (CDC/ATSDR).

Social equity is a key element of asset criticality but not explicitly captured in most criticality metrics. Resilience for historically underserved communities may not be properly captured in climate vulnerability assessments unless an agency is intentional about characterizing the vulnerabilities of these populations and addressing them explicitly with appropriate investments to reduce vulnerability and enhance resilience (Amekudzi-Kennedy et al. 2021). In particular, resilience tends to be defined not by the strongest elements of a system but by the weakest elements, which may cause the system failure or performance reduction with consequences that may extend to a broad range of users.

*Table 4. Factors for Estimating Criticality Score at GDOT**

	Criticality Score			
Criteria	1 Low Impact	2 Moderate Impact	3 High Impact	4 Very High Impact
AADT	Low	Medium	High	
Functional Classification of Roads	Unclassified Routes	U.S. Highways	U.S. Highways, Intermodal Corridors	U.S. Highways, Intermodal Corridors, Interstates
Number of Lanes	<4	>=4		
Governor's Road Improvement Program			Yes	
Evacuation Route			Yes	
STRAHNET/ STRAHNET Connectors				Yes
State Freight Corridors				Yes

*Criticality factors include the CDC/ATSDR Social Vulnerability Index

VULNERABILITY

Vulnerability is the degree to which a system is susceptible to, or unable to cope with adverse effects of climate change of extreme weather events. In the transportation context, climate change vulnerability is a function of the transportation system's exposure to climate effects, sensitivity to climate effects and adaptive capacity (FHWA 2017). This study estimates asset vulnerability (to the changing climate) as the product of climate hazard exposure, asset sensitivity and adaptive capacity (**Equation 2**). Because the hazard exposure variable incorporates spatial and temporal variation, we can think of it as a dynamic exposure variable which enables us to estimate dynamic vulnerability (that is, vulnerability that captures historical spatial and temporal changes in the various climate factors).

Climate Vulnerability = Climate Hazard Exposure * 1/Asset Condition * 1/Adaptive Capacity … Equation 2

RISK

Risk is defined as the chance (or probability) and consequences of loss (Fischhoff et al. 1984). Asset risk to the changing climate is estimated as the product of asset vulnerability and asset criticality, with criticality being used as a surrogate for the consequences of hazard exposure – due to the unavailability of damage cost information (**Equation 3**). Because the hazard exposure variable incorporates spatial and temporal variation, we can think of it as a dynamic exposure variable which enables us to estimate dynamic risk (that is, risk that incorporates the historical spatial and temporal changes in the various climate factors).

Climate Risk = Climate Hazard Exposure * 1/Asset Condition * 1/Adaptive Capacity * Asset Criticality … Equation 3

ASSET PRIORITIZATION FOR RESILIENCE TREATMENT

A four-by-four matrix is used to prioritize the assets and other elements of the system (e.g., corridors) based on the relative urgency of need for more detailed examination to address their general vulnerability to the changing climate. **Figure 7** shows the prioritization matrix for asset resilience treatment. The Vulnerability/Criticality Matrix is also proposed by TRB's Committee on Resilience Metrics in one of the three authoritative vulnerability assessment frameworks discussed earlier (**Section 2**) (TRB 2021). In Figure 7, the color gradient signifies dynamic risk, which is the product of criticality and dynamic vulnerability. The vulnerability calculated by this procedure is referred to as dynamic because it formally incorporates space-time variations of the hazards determined by conducting GIS-based hot spot analysis on historical data. So, rather than a binary exposure variable indicating the presence or absence of a hazard, the hot spot analysis procedure estimates a dynamic exposure variable in which the relative strength of hazard exposure is reflected in the exposure index score.

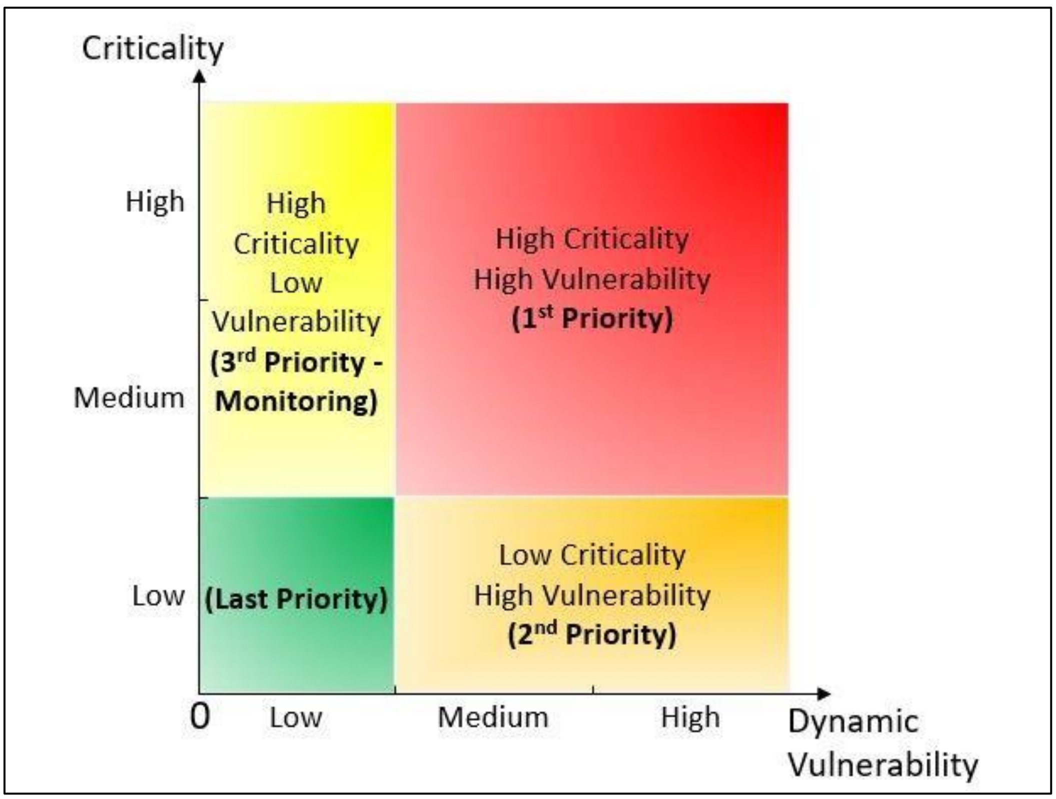


Figure 7. Matrix: Asset Prioritization using Dynamic Vulnerability and Risk

As Figure 7 shows, the high-criticality/high vulnerability assets fall into the highest priority category: these are also the highest-risk assets. The low-vulnerability assets are ranked lower in priority than the high-vulnerability assets, because the former are more resilient than the latter, all else being equal. In several agency systems, the low-criticality, high-vulnerability assets may include assets that are critical for underserved populations. In order to build resilience in a socially-equitably manner, it will be important to conduct another analysis to determine which assets or portions of the network in underserved communities deserve more immediate attention, to avoid leaving any communities behind in the agency's resilience building efforts.

Monitoring both climate exposure and asset condition can be important to determine in a timely manner when closer examination is necessary for particular assets or portions of the network, facilitating an efficient resilience planning approach. Low-vulnerability/low-criticality assets or portions of the network have the lowest risk and are therefore ranked in the lowest priority.

SPECIFIC EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY

While the approach discussed above focuses on general exposure and general sensitivity, the MHEVRA methodology can be applied to capture the exposure of assets to specific hazards, e.g., pavement exposure to inland flooding. In this case, the data for asset sensitivity, rather than being based on a general network condition index, would be based on the asset-hazard failure mechanism for the specific hazard of interest, e.g., bridge scour index. Likewise, adaptive capacity will be focused on specific structural and non-structural treatments to enhance resilience to this hazard, e.g., riprap and installation of gabions at the bridge abutments, stone pitching upstream from the foundation, and others to strengthen resilience to bridge scour. The specific vulnerability function will include specific exposure, estimated using the normalized score from the results of the hot spot anlaysis for the particular hazard. A total weight of 100% will be assigned to the specific condition resulting from the specific hazard, which will then be the basis for estimating asset sensitivity. In addition, the adaptive capacity will be tailored to the particular hazard of interest.

CLIMATE VULNERABILITY AND RISK ASSESSMENT – APPLICATIONS AND SIGNFICANCE

The section below presents examples of the results that can be generated using the MHEVRA Tool, and highlights their significance in resilience planning to enhance system performance.

Cumulative and Hot Spot Analysis

The MHEVRA Tool conducts cumulative and hot spot analysis for all the hazards shown in **Table 2**. **Figures 8 and 9** show the cumulative count (1960-2020) and hot spots (1990 – 2020) for thunderstorms. The presence of hazards in a particular county and the hot spot analysis results of these hazards are inputs to the determination of general and specific hazard exposure as shown in **Tables 1 -3**.

Asset Exposure, Sensitivity, Criticality, Vulnerability and Risk Analysis

Figure 10 depicts pavement exposure, sensitivity, criticality, vulnerability and risk. The methodology generates similar results for bridges and culverts. The approach may be extended to other assets using appropriate datasets, in the future. Pavement vulnerability is the product of pavement exposure, sensitivity and adaptive capacity. Adaptive capacity is estimated at the district level and assigned a unit baseline value for all of GDOT's seven transportation districts, assuming that all districts are at the beginning stage of resilience planning. Pavement risk is a product of pavement vulnerability and criticality. The development of vulnerability and risk results at the district level, useful for asset prioritization for resilience treatments, also provides insights into equitable treatments from the standpoint of the different districts, e.g., more urban versus more rural districts. **Social equity is critical to the development of resilience and must be approached to ensure no one is left behind as resilience within the system is developed.** The MHEVRA Tool generates these outputs for bridges and culverts as well.

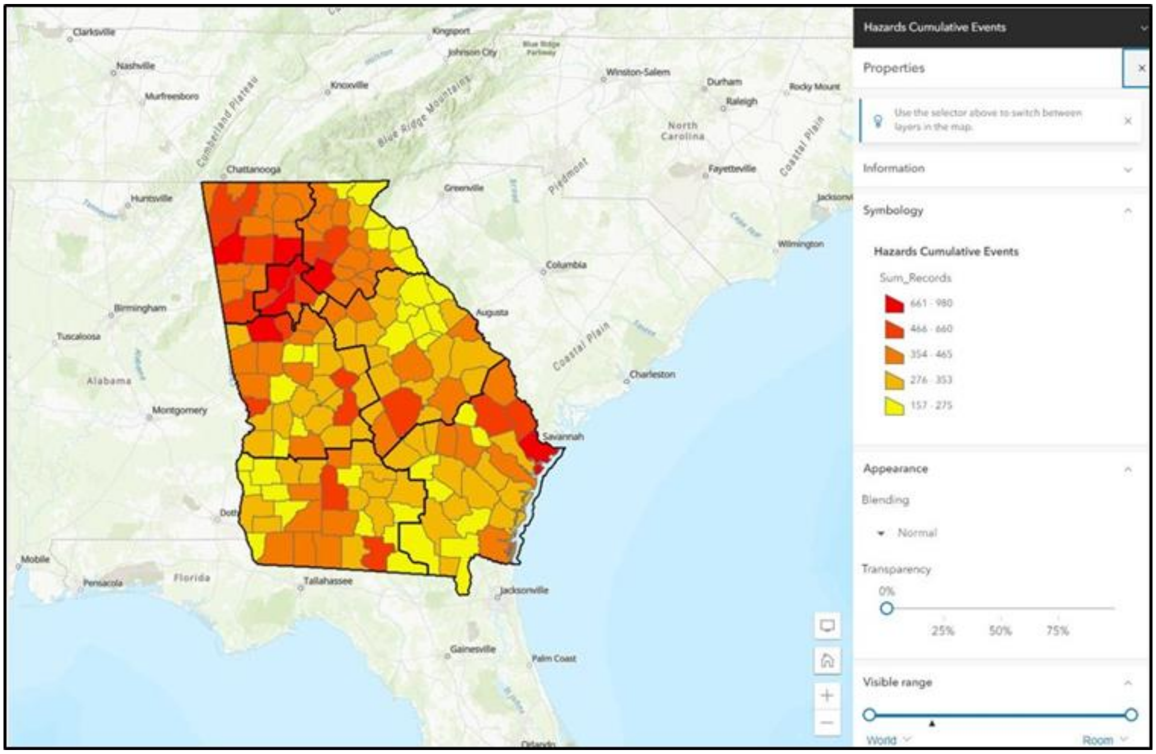


Figure 8. Map. Cumulative Thunderstorm Events (1960-2020) (MHEVRA Tool/SHELDUS)

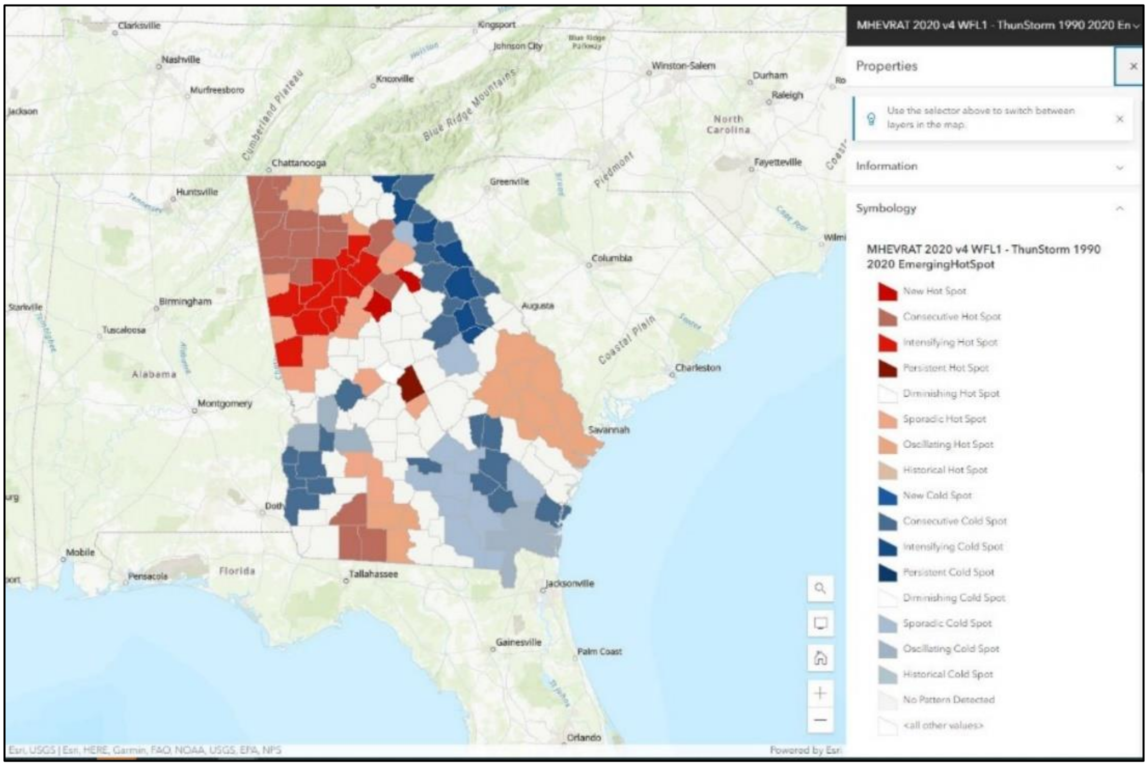


Figure 9. Map: Thunderstorm Hot Spots (1990-2020) (MHEVRA Tool/SHELDUS)

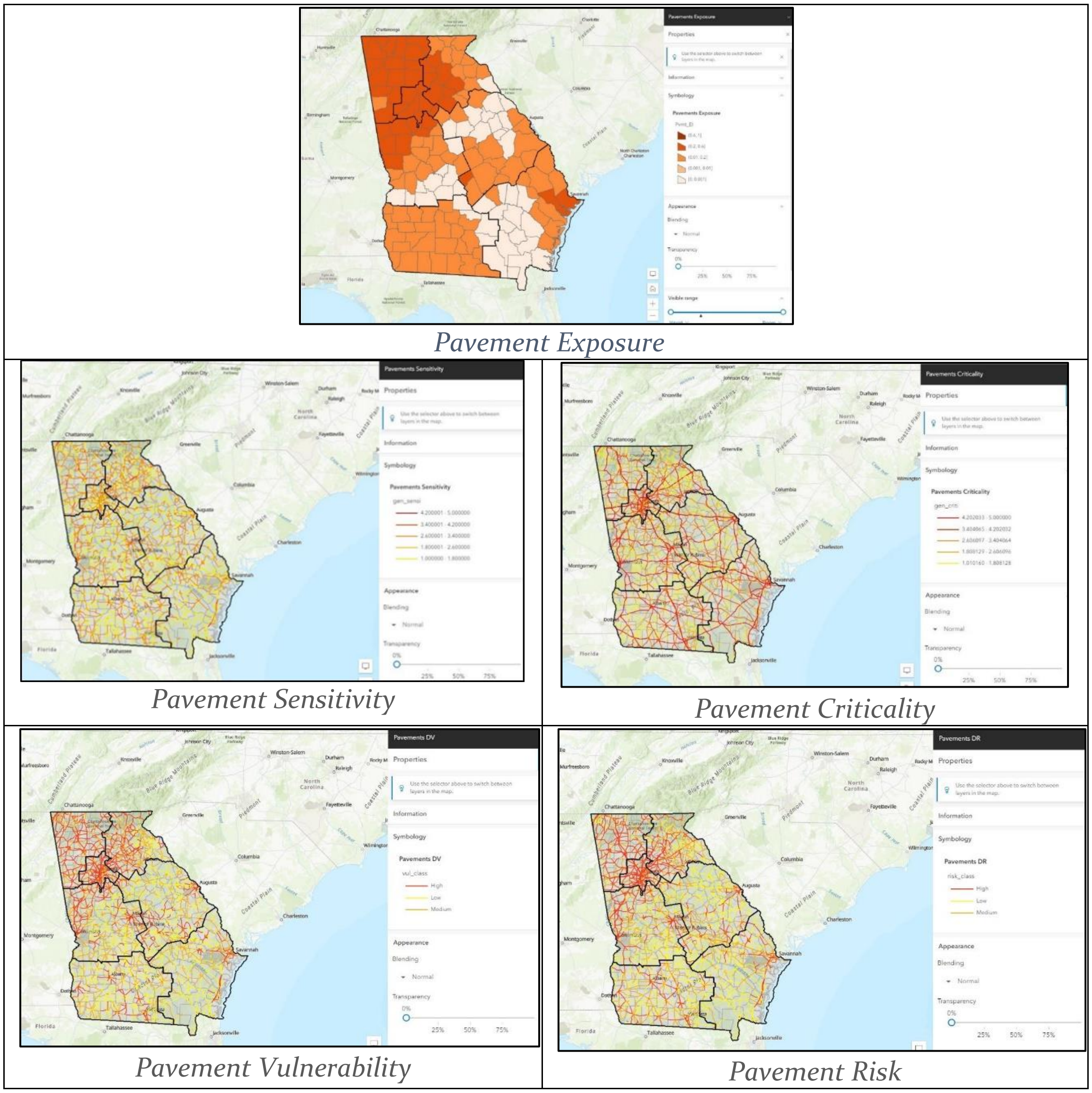


Figure 10. Maps. Pavements - General Exposure, General Sensitivity, Criticality, General Vulnerability and General Risk (MHEVRA Tool/SHELDUS)

Asset Prioritization for Resilience Treatment

Figures 11 and 12 illustrate asset prioritization by vulnerability and criticality (see **Figure 7**) with state and district level views. These outputs show where the critical vulnerabilities are in the infrastructure system and where there is a need for closer examination using more detailed data as well as information from practitioners and stakeholders. The prioritization charts and graphs provide a spatial view as well as distribution of the assets based on their resilience improvement needs.

Figures 11and 12 provide the first level of prioritization in climate vulnerability and risk assessment, drawing the practitioner's attention to the most vulnerable assets that require closer examination to determine appropriate resilience treatments. These figures also highlight the distribution of resilience needs across the state and across the different GDOT districts, providing information that can be used in determining socially-equitable resilience treatments by transportation district as resilience building progresses – particularly for consideration of socially-equitable investments across more urban and rural counties. Similar efforts highlighting underserved communities will provide more viable data for addressing the unique transportation needs of underserved communities. Such data is being developed in a separate project, funded by the US Department of Transportation Center for Transportation, Equity, Decisions and Dollars, and supported by GDOT (Amekudzi-Kennedy et al. 2023).

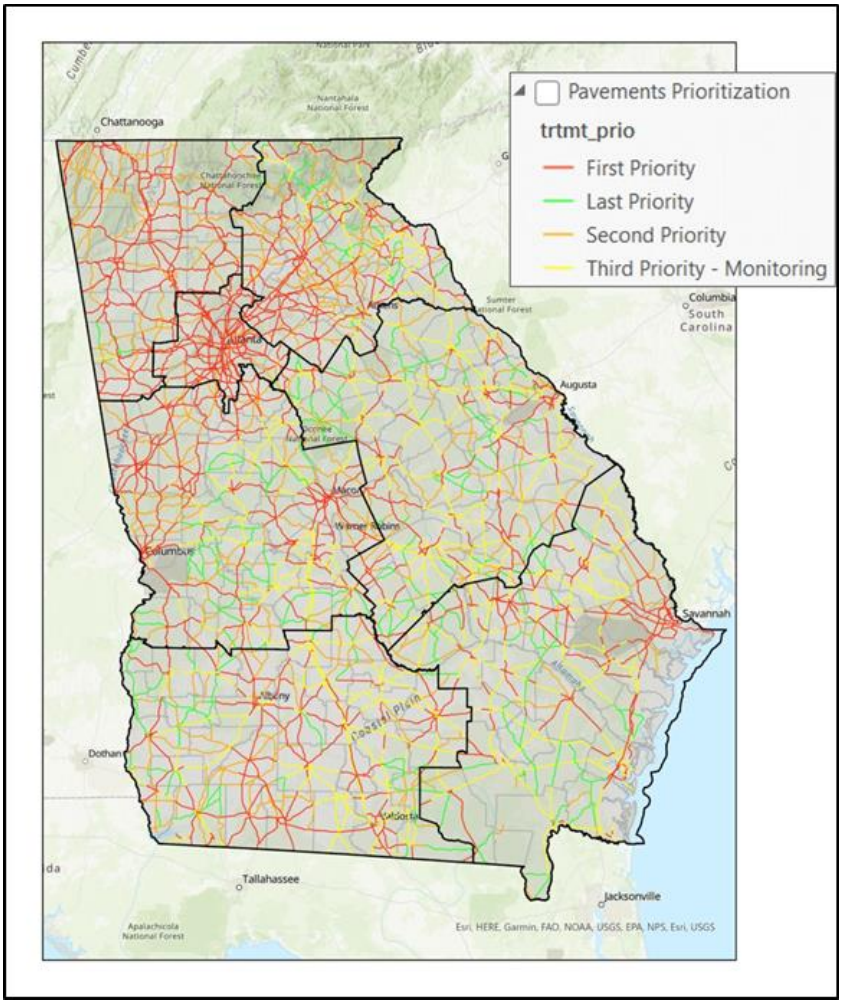


Figure 11. Map: Pavements - Prioritization by Vulnerability and Criticality - Spatial State and District Level Views (MHEVRA Tool/SHELDUS)

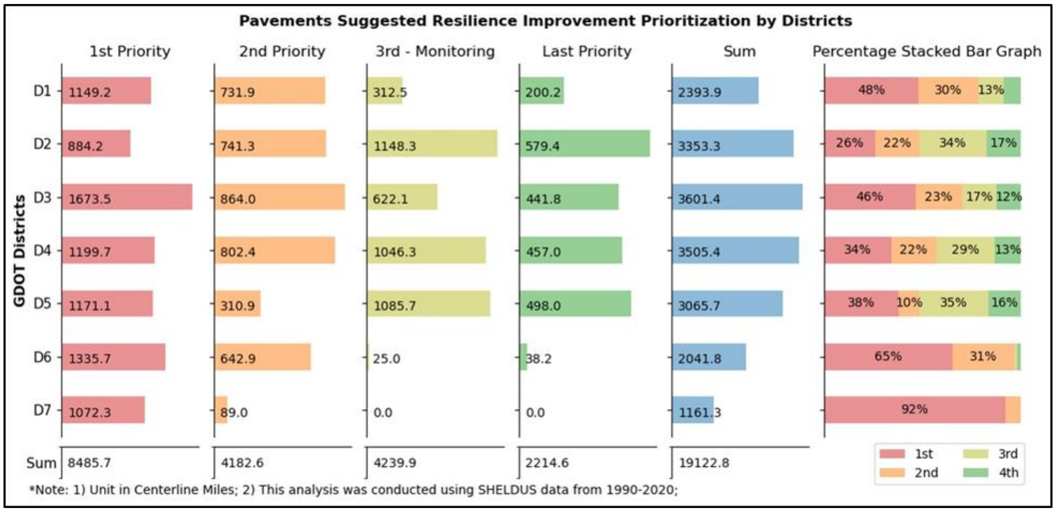


Figure 12. Graph: Pavements - Prioritization by Vulnerability and Criticality - District-Level View (MHEVRA Tool/SHELDUS)

System Resilience Performance Monitoring and Management

Monitoring asset exposure to climate hazards, asset sensitivity, vulnerability and risk over time will give practitioners useful information concerning whether the system is becoming more resilient or less so. Vulnerability and risk reduction over time will indicate the system is becoming more resilient; however, these are not the only metrics for measuring resilience as discussed in **Section 7** below. As agencies invest in resilience building, practitioners should expect vulnerability distributions and risk distributions as shown in **Figures 13 and 14** to shift to the left – reflecting a reduction in overall system vulnerability and risk. The MHEVRA methodology provides vulnerability and risk distributions for all assets included in the climate vulnerability/risk assessment.

Furthermore, agencies that decide to link their carbon reduction strategies with their resilience strategies can identify additional opportunities to integrate shorter-term resilience and longer-term sustainability initiatives better in order to achieve more sustainable resilience in the longer term - by addressing both the effects and causes of the changing climate. Figures 11.1 and 11.2 show the pavement vulnerability distribution, and, the bridge risk distributions for the state and for GDOT's seven districts, in each case. These distributions, generated periodically, for example whenever the SHELDUS data is updated (annually), or biennially, will enable the agency to monitor and track how system resilience is changing over time.

GDOT_DISTR	Pvmt_low	Pvmt_medi	Pvmt_high	Pvmt_sum	Pvmt_low	Pvmt_medi	Pvmt_high
1	362.5	888.5	1142.9	2393.9	15%	37%	48%
2	1546.9	1022.2	784.2	3353.3	46%	30%	23%
3	1063.9	1378.6	1158.9	3601.4	30%	38%	32%
4	1811.3	1108.8	585.3	3505.4	52%	32%	17%
5	1583.6	1046.0	436.0	3065.7	52%	34%	14%
6	0	663.5	1378.3	2041.8	0%	32%	68%
7	0	272.0	889.3	1161.3	0%	23%	77%
State Sum	**6368.2**	**6379.6**	**6374.9**	**19122.8**			

Note: Unit in Centerline Miles

Figure 13. Chart: Pavement Vulnerability Distributions for the State of Georgia and for GDOT's Seven Districts (MHEVRA Tool/SHELDUS)

GDOT_DISTR	Brdg_low	Brdg_medi	Brdg_high	Brdg_sum	Brdg_low	Brdg_medi	Brdg_high
1	323	384	452	1159	28%	33%	39%
2	497	453	165	1115	45%	41%	15%
3	570	606	488	1664	34%	36%	29%
4	945	316	142	1403	67%	23%	10%
5	739	454	138	1331	56%	34%	10%
6	28	439	823	1290	2%	34%	64%
7	18	465	911	1394	1%	33%	65%

Figure 14. Chart: Bridge Risk Distributions for the State of Georgia and for GDOT's Seven Districts (MHEVRA Tool/SHELDUS)

In addition to general climate vulnerability and risk assessments, the MHEVRA Tool can also conduct specific climate vulnerability and risk analysis, with data inputted for a specific climate hazard and a specific asset, e.g., bridge scour; using data on the relevant asset-hazard failure mechanism(s), e.g., bridge scour index, and using appropriate information on the agency's adaptive capacity to the specific hazard. **Figure 15** illustrates the vulnerability of bridges to scour as a result of inland and coastal flooding. The MHEVRA methodology supports a relatively

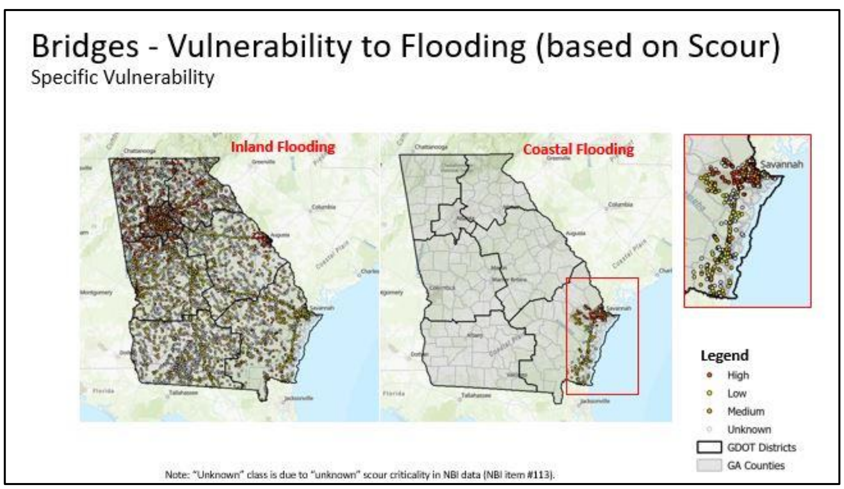


Figure 15. Map: Specific Vulnerability of Bridges to Scour caused by Inland and Coastal Flooding (MHEVRA Tool/SHELDUS)

robust risk-based approach to climate vulnerability assessment and risk analysis for transportation assets. It will be strengthened by the future integration of downscaled climate projection data to complement the SHELDUS data. It will also be enhanced by introducing system operational analysis to identify and prioritize portions of the network where redundancy is needed to strengthen system resilience.

5 CLIMATE ADAPTATION GUIDEBOOK FOR TRANSPORTATION PRACTITIONERS

OVERVIEW

Once transportation assets or sections of the network are prioritized for closer examination to determine appropriate resilience strategies, the **Climate Adaptation Guidebook for Transportation Practitioners** was developed in this study to facilitate climate adaptation in transportation planning (Tennakoon 2023, Tennakoon et al. 2023). The Guidebook presents a centralized database of adaptation options and strategies, with a focus on effective practices for adaptation planning. The portfolio of climate adaptation strategies and effective practices are sorted according to various asset-hazard pairs intended to aid GDOT's Transportation Planners and District Engineers with identifying and prioritizing appropriate adaptation strategies for pavements, bridges and culverts. Strategies are offered on a district-by-district basis based on contextual hazard exposure and vulnerability.

The Guidebook thus assembles a range of adaptation planning guidelines, frameworks, and effective practices into one comprehensive document for the purposes of easy access and reference to adaptation information. Despite an abundance of resilience-related information, such information is often scattered and difficult to access. It is also rarely presented in a manner that enables identification and evaluation of contextual factors. Therefore, the Guidebook bridges these gaps by compiling context-specific adaptation information, and presenting it in a user-friendly, easily navigable document. The Guidebook should be updated periodically to ensure the agency has access to best and emerging practices.

DEVELOPMENT

The Guidebook was developed by conducting a series of document reviews including state and federal adaptation plans and frameworks, state DOT plans, emerging literature on adaptation options and strategies for transportation infrastructure, reports detailing adaptation projects, and other sources of information. Furthermore, multiple search terms pertaining to the subject were used to explore the literature in transportation and transportation-related journal databases such as the American Society of Civil Engineers (ASCE), the Transportation Research Record (TRR), Road Materials and Pavement Design (RMPD), and other sources. In addition, the Multi-Hazards Exposure, Vulnerability and Risk Analysis (MHEVRA) Tool (Yang & Amekudzi-Kennedy 2023) was applied to generate context-specific information as indicated above. The tool was used to evaluate the hazard contexts for the various GDOT Districts in order to understand better the impact of climate change and related hazards on the Districts' transportation infrastructure.

APPLICATION

Results from the MHEVRA Tool are applied in the Guidebook in a manner that is useful to GDOT's Planning Officials and District Engineers. After evaluating the relevance of hazards for each of GDOT's seven districts, the asset-hazard matrix presented in **Table 2** was adjusted for each district in order to present only information relevant to the district - based on past hazard exposure and emerging trends from the hot spot analysis. **Figure 13** below depicts the sequence of steps to access information in the Guidebook - for easy navigation, information finding and application.

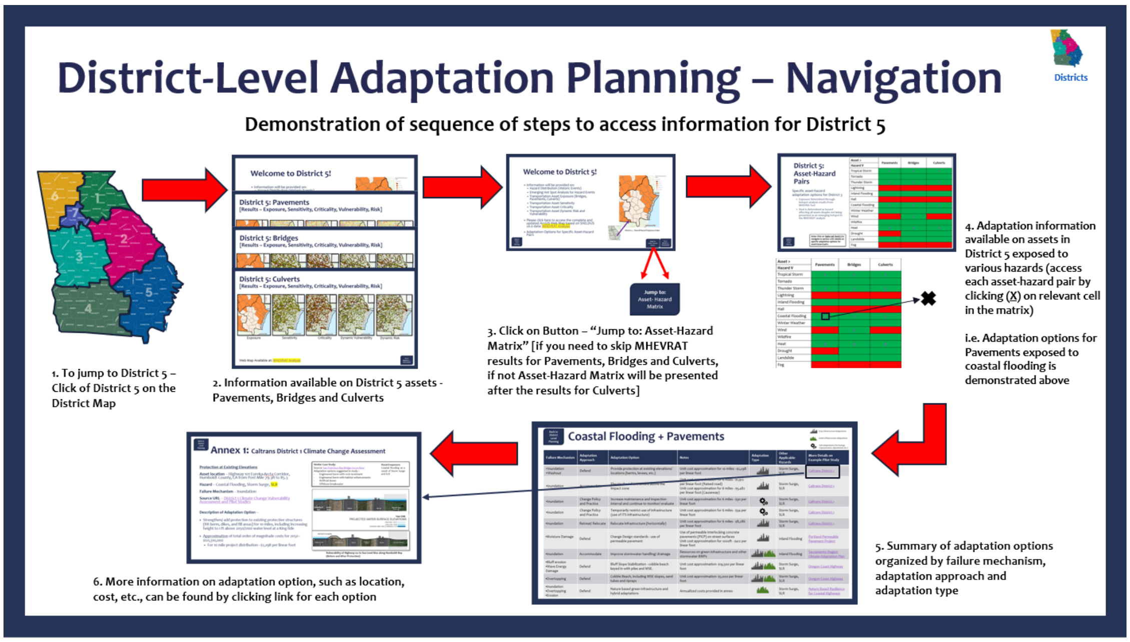


Figure 16. Matrix: Sequence of Steps for Navigating the District-Level Adaptation Planning Section of Guidebook (Tennakoon et al. 2023)

A 188-page-long document, the Guidebook presents climate hazard exposure, asset sensitivity, criticality, vulnerability and risk data for the state of Georgia and GDOT's seven districts' pavements, bridges and culverts. The Guidebook then offers contextually-relevant gray infrastructure, green infrastructure and policy-based adaptation strategies for consideration by state and district practitioners, together with examples of successful applications across the U.S. and internationally, case studies of those applications, and, associated cost data, where available.

The strategies are presented in the following four areas:

- Defend;
- Accommodate;
- Retreat, and,
- Make changes in policy and practice.

BROADER CONSIDERATIONS – ADAPTING INTERDEPENDENT SYSTEMS

Using flooding as the threat of study, a paper was developed in the study to highlight the importance of considering system, organization and project interdependencies while pursuing climate adaptation (Cuadra et al. *In Press*). The document emphasizes that current adaptation practices often take the form of hard, protective measures, implemented exclusively on transportation assets with little coordination with external agencies. Consequently, the results are often overly expensive, offer incomplete protection, and can result in catastrophic failures across multiple infrastructure systems. And, although more effective practices exist, they remain poorly inventoried and are often too general or case-specific to be broadly useful. The paper offers useful suggestions for practice at the system, organization and project levels.

At the system level, adaptations addressing vulnerabilities across multiple systems (e.g., stormwater and transportation) can strengthen infrastructure against cascading failures and improve efficiencies in adapting interdependent networks. At the organization level, teams that self-reorganize to fit project adaptation needs were found to be more effective in responding to change and overcoming difficulties in adaptation implementation. And, at the project level, anticipating and addressing causal relationships between infrastructure and the environment was found to improve the reliability of adaptations against catastrophic failure. Such practices, compared to the traditional implementation of hard, defensive measures, were found to yield co-benefits, and to be more reliable in the long run.

6 PROJECT PRIORITIZATION INCORPORATING RESILIENCE CONSIDERATIONS

MULTIPLE CRITERIA METHODS (SHORTER-TERM APPROACH)

The STIP-X (10-yeat State Transportation Improvement Program) is a relatively new prioritization mechanism for transportation projects. To complement the current draft of the STIP and ongoing efforts at GDOT to develop a project prioritization method for the STIP-X, a multiple criteria evaluation resource was developed in this study to highlight opportunities to incorporate resilience, equity and funding considerations in project prioritization. The novelty of this approach lies in the **flexibility of the prioritization metrics** which are simultaneously targeted to optimize the return on specific funding opportunities as well as address the resilience and social equity improvement needs of particular assets or portions of the network (Garrett 2023, Garrett et al. 2023c).

The decision-support resource's broader decision criteria categories for the multiple criteria evaluation are as follows:

(1) Freight Mobility and State Priorities
(2) Economic Vitality
(3) Safety and QOL
(4) Future Mobility Ready, and,
(5) Preservation, Resilience and Criticality.

The Multiple Criteria Prioritization resource breaks each of these areas down into prioritization measures and links them to relevant data sources within the tool. For example, the Freight Mobility and State Priorities includes two metrics - one for Freight Movement, and the other for State Priorities. The Freight Movement metrics include Freight Corridor and Intermodal Facilities & Trade Gateways, where one examines whether the project is located along the National Multimodal Freight Network, and the other where one looks at the proximity of the project to intermodal facilities. The State Priorities metric incorporates considerations from the Governor's Road Improvement Program (GRIP) and the Georgia Ready for Accelerated Development (GRAD) certified sites.

After the metrics are presented, relevant federal funding grants and programs are highlighted with links to relevant online federal government information. For the Freight Mobility and State Priorities area, for instance, examples of two major grant opportunities are the "Infrastructure for Rebuilding America" (INFRA) grant and the "Consolidated Rail Infrastructure and Safety Improvement" (CRISI) grant from the Infrastructure Investment and Jobs Act.

The major contribution of this tool is the emphasis on **flexible metrics** that should always be kept up-to-date as transportation and infrastructure legislation are passed, new policies are made and new funding sources made available, to link metrics appropriately to the critical priorities and supporting funding sources. To maximize its value, this resource must therefore be kept updated relative to the transportation and infrastructure institutions (that is, laws, policies and regulations). **Table 5** shows the broad priority metric categories with default weights by project type, each of which is linked with the relevant federal-level and state-level funding opportunities.

Table 5: Flexible Project Prioritization Metrics Including Resilience and Equity Considerations

	Weights by Project Type			
Criteria	**Asset Management Projects** (Pavement, Bridge, and Culvert)	**Infrastructure Projects** (Safety, Mobility, Capacity, and TSMO)	**Bicycle, Pedestrian, and Non-Motorized Infrastructure Projects**	**Public Transit Projects**
Freight Mobility and State Priorities - **Freight** Movement - State Priorities	20%	20%	0%	0%
Economic Vitality - Workforce - **Tourism** - Underserved Populations*	20%	20%	25%	25%
Future **Mobility** Ready *Dependent on Project Type*	20%	20%	25%	25%
Safety and **Quality of Life** - Crashes - Safety Projects - **Environmental** Impacts - Health Impacts	20%	20%	25%	25%
Preservation, Resilience, and Criticality - Infrastructure Quality - Consequence of Conditional Failure	20%	20%	25%	25%
Total	100%	100%	100%	100%

MODIFIED RESILIENCE TRIANGLE METHOD (LONGER-TERM APPROACH)

The Modified Resilience Triangle Method was developed for project prioritization to present a **flexible approach to evaluating the long-term benefits** of building adaptive capacity in order to enhance resilience in various infrastructure systems under future uncertainty (Singh 2022, Singh et al. 2023). The methodology uses long-timeframe assessment methods based on net present value methods and approaches to quantify different levels of uncertainty, along with multi-criteria assessment methods.

The approach is demonstrated using three different case studies where investments have focused on different aspects of adaptive resilience in infrastructure systems. The results show the increasing benefits of adaptive strategies over time with ongoing learning and the evolving nature of resilience needs (**Figure 17**). While this methodology produces useful outputs for decision making, it is heavily data intensive. The methodology is therefore recommended for projects of the highest significance where the agency wants to maintain high levels of resilience come what may.

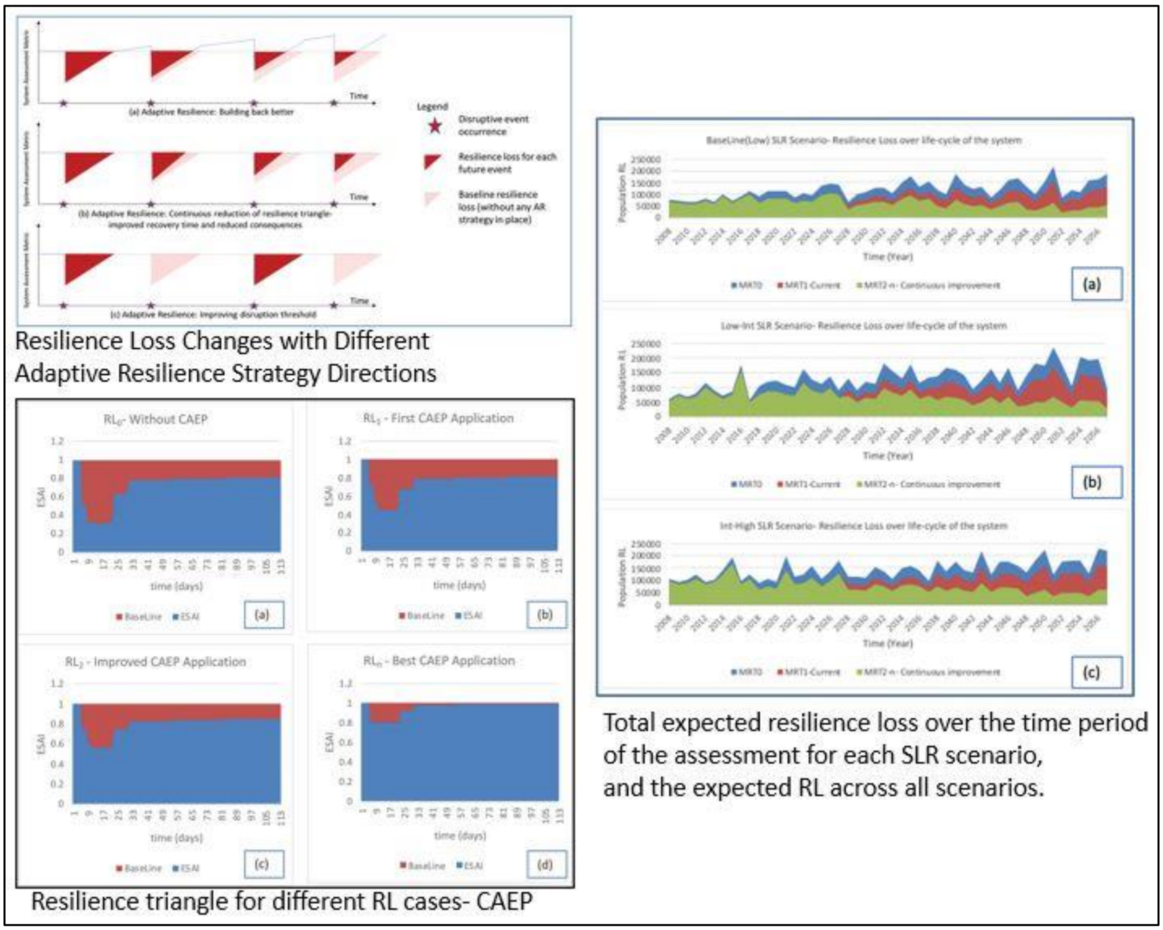


Figure 17. Graph: MRT Output - Resilience Losses and Benefits for Various Case Study Scenarios (Singh et al. 2023)

7 CLIMATE RESILIENCE METRICS

OVERVIEW: METRICS AND INDICATORS RECOMMENDED BY TRB, AASHTO AND FHWA

Three authoritative documents from the Transportation Research Board, American Association of State Highway and Transportation Officials, and the Federal Highway Administration provide guidance on climate vulnerability assessment and resilience measurement (TRB 2021, AASHTO 2021, FHWA 2017).

The **AASHTO** guidance proposes the following resilience maturity questions as an indicator of how resilient an agency is:

- Have you characterized the vulnerability of each asset to each hazard?
- Have you characterized the vulnerability of each asset for all potential hazards/threats and hazard/threat combinations?
- Have you developed a prioritized list of vulnerable assets?
- Have you communicated prioritization of assets to agency staff and external constituencies?

The **FHWA** guidance recommends leading a climate vulnerability assessment with criticality and then using a criticality screening to hone vulnerability assessment and metrics. It also recommends two approaches split between practitioner workshops and indicator scoring. Risk is considered a product of vulnerability and severity of consequences.

The FHWA guidance suggests the following metrics for initial screening:

- Age, relative to design life
- Level of use (e.g., volume to capacity ratio)
- Replacement costs
- Maintenance schedule, cost, and effort
- Evacuation route status
- Materials information and sensitivity
- Pavement quality
- Asset redundancy to system

Criticality measures include the following:

- AADT
- Functional class
- Goods movement throughput (monetized if possible)

- Access to employment, educational and medical centers
- Use and reliance on by emergency response and services

Analysis indicators gathered through example studies include the following:

- Sea-level rise
- Temperature differences from climate change
- Stream flow and velocity where running water is relevant
- Asset elevation
- Existing asset protections
- Truck traffic volume (as a sensitivity measure for heat-softened pavements)
- Proportional change in design flow required to overtop bridges or culverts
- Channel condition rating
- Culvert condition rating
- Historical flooding issues
- Drainage area ground cover proportions (e.g., impermeable pavement cover)
- Road subbase subsidence
- Road embankment subsidence
- Road friction loss when wet
- Underpass flooding

In addition to the usual local users of transportation infrastructure, proposed areas of expertise for workshop participants include the following:

- Asset Management
- Maintenance and Operations
- Emergency Management
- Engineering
- Materials
- Hydrology
- Geology
- Climate Science

The report also proposes a few resources for further reading, all available online to the general public:

- 2013-2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned and Recommendations (FHWA 2016)
- Gulf Coast Vulnerability Study (USDOT 2008-2015)
- Vulnerability Assessment Scoring Tool (VAST) (FHWA 2015)
- ROADAPT Guideline B (CEDR 2016)

- ROADAPT Guideline C (CEDR 2016)

The **TRB** guidance follows an outcome-based approach and notes that the most accurate method for resilience measurement is taking integrals of functionality over time, and tracking the deficit of functionality as shocks are experienced. It also recommends numerical simulation to measure recovery curves under different scenarios, in particular recommending testing many recovery curves against a standard for recovery rate. This way, a system's probabilistic resilience could be measured as the probability of satisfying recovery rate standards across many scenarios. For example, a simulation in which a road is cleared and recovered with a functionality curve above the standard curve in four out of five modeled scenarios would be said to have an 80% rate of resilience satisfaction.

The study recommends two tools for resilience measurement:

- Interdependent Networked Community Resilience Modeling Environment (IN-CORE), accessible to the general public online (COE); and,
- Probabilistic Resilience Assessment of Interdependent Systems (PRAISys), also accessible to the general public online (The PRAISys Project).

The IN-CORE platform implements measurement science enabling users to run scientific analyses that model the impact of natural hazards and resiliency against the impact on communities (COE). The PRAISys platform enables post-event resilience analysis of communities by addressing stochastic interdependencies among infrastructure systems in a probabilistic manner (The PRAISys Project).

The TRB guidance also provides a table of functionality metrics primarily concerned with the rate at which facilities are serviceable, their throughput of goods and passengers, and the number of facilities accessible at any time during operation. The measures are summarized below:

- General: capacity, delay, safety
- Roads: connectivity, link length, pavement serviceability, ITS up/down time
- Regional rail: ITS up/down time, time proportion with power, station open/closed proportions
- Freight rail: track serviceability, ITS up/down time, terminal open/closed proportion
- Intermodal transit terminal: connectivity, number of transport modes in operation at time, terminal open/closed proportion, terminal throughput, ITS up/down time, time proportion with power
- Active transport: special purpose lane open/closed proportion, sidewalk accessibility, parking and mobility service accessibility

- Air travel: connectivity, number of transfers, airport rate of take-offs/landings, on-time performance, fuel availability
- Waterways: connectivity, travel speed, dock/port open/closed proportion, link speeds, lock capacity, lock open/closed proportion
- Pipelines: flow rate/throughput rate, storage facility capacity, storage facility status, and,
- Intermodal facilities with waterways: status, service times, ITS up/down time, throughput of goods.

SYSTEM-LEVEL RESILIENCE METRICS

This study proposes application of the MHEVRA Tool on a periodic and ongoing basis to track system-level performance measures that communicate the extent to which climate vulnerability reduction is occurring, as well as how the agency is reducing its carbon footprint for long-term sustainability (**Table 6**). The monitoring effort will seek to answer the following questions:

- How is system risk changing over time?
- How is system vulnerability changing over time?
- How is adaptive capacity changing over time?
- How is system sensitivity changing over time?
- How are carbon emissions changing over time?

Table 6. System-Level Resilience Metrics using the MHEVRA and other Tools

System Indicators	What they measure	Desired Direction	Data Source(s)
Vulnerability	Distribution of vulnerability of assets to area's hazards	Left (Vulnerability Distribution) i.e., Lower Vulnerability	Climate Vulnerability Assessment results
Risk	Distribution of risk of assets to area's hazards	Left (Risk Distribution) i.e., Lower Risk	Climate Risk Analysis Results
Vulnerability-and-Risk	Distribution of assets across High Risk-High Vulnerability, Low Risk-High Vulnerability, High Risk-Low Vulnerability and Low-Risk, Low Vulnerability categories	Reduce % of High-Risk, High-Vulnerability assets (via prioritization and implementation of resilience improvement strategies.)	Climate Vulnerability Assessment Results Climate Risk Analysis Results
Adaptive Capacity	Capabilities of agency/ system to adapt to become more resilient	Up	Adaptive Resilience Capability Maturity Model (AR-CMM), Resilience Rating Tool & Scorecard, Response times, Detour lengths, Status on Building Back Better
Sensitivity	Distribution of asset sensitivity to area's hazards	Down	Asset condition data
Carbon Emissions	Carbon Emissions (per capita and total) for agency and system	Down	Varied including the US Environmental Protection Agency's Inventory of U.S. GHG Emissions and Sinks

Figures 13 and 14 show examples of MHEVRA-generated climate vulnerability and risk distributions.

PORTFOLIO MEASURES FOR GENERAL RESILIENCE CAPABILITIES

This study assembled a portfolio of resilience metrics from the literature to help transportation agencies readily identify input, activity and output measures for four resilience capabilities: preparedness, robustness, recovery and capacity to reorganize (Williams et al. *IRG Working Paper Series*). This resource may be used to supplement the recommended AASHTO/TRB/FHWA metrics (**see Section 7.1**) and extended by various departments within a transportation agency for resilience tracking, measurement and planning. **Table 7** depicts the organization of the portfolio of resilience metrics.

Table 7. Portfolio of Resilience Metrics Organized by Common Resilience Capabilities

Measures	Resilience Abilities: PREPAREDNESS	ROBUSTNESS	RECOVERY	CAPACITY TO REORGANIZE
INPUTS	Measures of resources available to the system and awareness of stakeholders to be prepared for an event	Measures of the physical attributes of the system that determine how well it can withstand hazards	Measures of emergency resources available to the system and budget allocation to ensure proper recovery	Measures of the physical attributes of the system that determine how flexible it can be to maintain functioning
ACTIVITIES	Measures of the actions being taken to make sure the system is prepared for an event	Measures of inspections and improvements being performed to ensure the system can withstand hazards	Measures of how effectively the system communicates with the public in order to recover and restore function	Measures of actions the system is taking to establish a more multi-modal system that can allow for adaptability
OUTPUTS	Measures of how well the system has been prepared for events in the past or in simulations	Measures of how well the system responds and maintains functioning during the aftermath of an event	Measures of how well the system responds over time after the event to recover to an acceptable state	Measures of how well the system responds over time as it adapts and reorganizes in the aftermath of the event
OUTCOMES	Measures of how safe, reliable, and equitable the system is as a result of it being resilient in the areas of preparedness, robustness, recovery, and capacity to reorganize			

(Williams et al. IRG Working Paper Series)

RESILIENCE RATING TOOL AND SCORECARD

Drawing from the World Bank's Resilience Rating System methodology (World Bank 2021), the Resilience Rating Tool and Scorecard (**Figure 18**) was developed in this study to enable assessment of a resilience rating reflecting the current level of development of vulnerability assessment and reduction and other resilience capabilities at a transportation agency. This tool therefore supports holistic resilience building in a transportation system – that is, resilience building to both known and unknown threats, focused on the organization and the physical transportation system.


Resilience Rating Tool

SELF-ASSESSMENT TOOL TO ASSESS CURRENT RESILIENCE RATING- TO SUPPORT HOLISTIC RESILIENCE DEVELOPMENT AT GDOT

The rating tool has been developed to assess the system at two scales – at the district level, and at a more granular scale of area offices within each district.

The self-assessment tool can be accessed and distributed using the links and the QR codes provided below for each scale of assessment.

The QR code can be used to distribute the tool via offline methods such as pamphlets, posters, and hard copy of reports distributed across offices at GDOT. The links may be used to share the tool via online methods such as email and social media.

District Level Assessment Tool

QR Code

Link
https://gatech.co1.qualtrics.com/jfe/form/SV_ehbiKcF5tzzoA3c

Area Office Level Assessment Tool

QR Code

Link
https://gatech.co1.qualtrics.com/jfe/form/SV_cAUgTQkUCVeVq5e

Figure 18. Document: Access Information for Resilience & Scorecard

The rating tool was developed to assess the transportation system at two scales: the district-level, and the more granular scale of area offices within each district. The self-assessment tool may be accessed and distributed using the QR codes provided for each assessment scale. The QR code may be used to distribute the tool via offline methods such as pamphlets, posters and hard copy reports. The links may be used to share the tool via online methods such as email and social media.

ADAPTIVE RESILIENCE CAPABILITY MATURITY MODEL (AR-CMM)

The Adaptive Resilience Capability Maturity Model (AR-CMM) was developed in this study to enable self-assessment and planning to enhance adaptive capabilities that strengthen resilience within a transportation agency (Singh 2021, Singh et al. 2022).


ADAPTIVE RESILIENCE CAPABILITY MATURITY MODEL

SELF-ASSESSMENT AND GUIDANCE TOOL TO SUPPORT HOLISTIC RESILIENCE DEVELOPMENT AT GDOT

The self-assessment and guidance tool can be accessed and distributed using the link and the QR code provided below. The QR code can be used to distribute the tool via offline methods such as pamphlets, posters, and hard copy of reports distributed across offices at GDOT.

The link can be used to share the tool via online methods such as email and social media.

QR CODE

ANONYMOUS LINK

https://gatech.co1.qualtrics.com/jfe/form/SV_bQQgNgMnvEOTAwu

Figure 19. Document: Access Information for Adaptive Resilience Capability Maturity Model

The tool facilitates the identification and strengthening of fundamental capabilities (five strategic, five programmatic, and six tactical) within a transportation agency and system that foster general adaptive resilience under uncertainty, and provides recommendations to practitioners to strengthen these capabilities – in so doing, strengthening its adaptive capacity. **Figure 19** provides information for accessing the tool.

Adaptive Capacity refers to the ability of a system to respond proactively and positively to stressors or opportunities by self-organizing or changing endogenously, during the response and recovery period (Manyena et al. 2019). **Adaptive Resilience** is the ability to continually adapt and cope with a frequently changing or uncertain environment (BeldingTraining). A detailed description of development of the tool is available in Singh (2021).

FLEXIBILITY/AGILITY SCORECARDS

Flexibility and Agility Scorecards (Garrett 2023, Garrett et al. 2023c) were developed in this study to enable transportation agencies to introduce flexibility and agility into their long-range transportation plans. **Flexibility** is the ability to respond in an effective way, in terms of performance, cost and time, to predictable or unpredictable changes that occur. **Agility** is the ability to adapt systems and services quickly, effectively and consistently when confronted with internal or external uncertainties, negative consequences, or positive opportunities.

Flexibility and agility are both described as precursors for adaptive capacity. Therefore, a transportation agency may apply the flexibility and agility scorecards to enhance its adaptive capacity and thus resilience – both for the organization and the physical infrastructure system. **Figure 20** depicts the kind of output generated by the Flexibility and Agility Scorecards. As shown in Figure 19 above, the Flexibility & Agility Scorecards provide standard, emerging and best practice examples from the 51 state DOTs to highlight various levels of practice for eight flexibility capabilities and six agility capabilities.

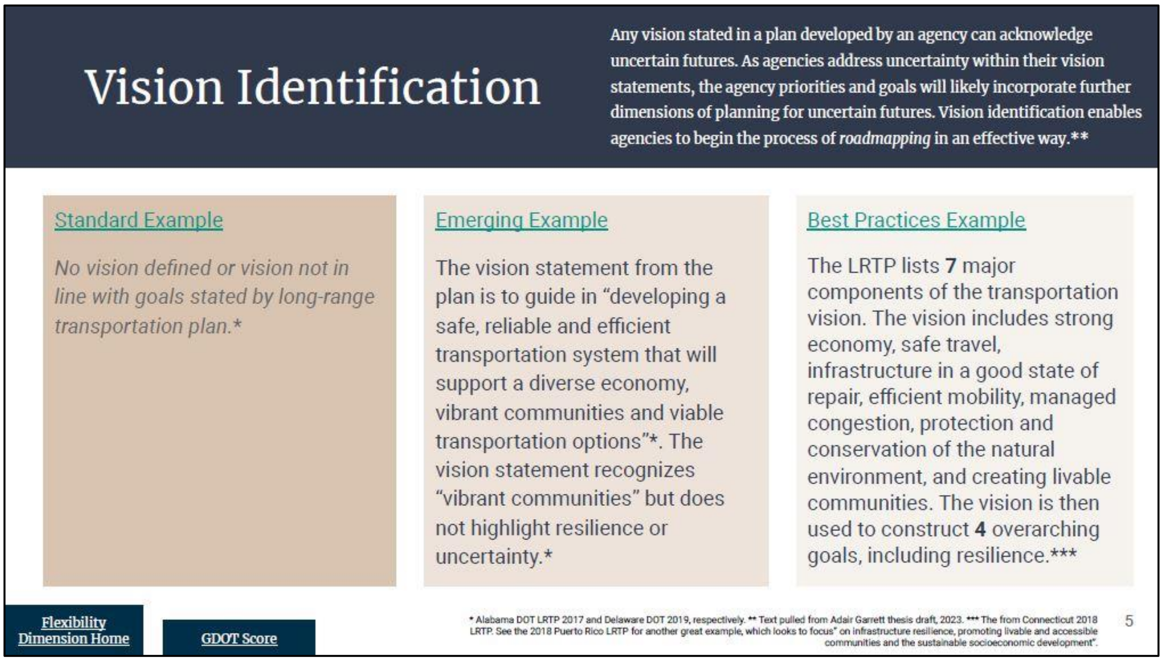


Figure 20. Scorecard: Example Application of Flexibility & Agility Scorecards (Garrett 2023, Garrett et al. 2023)

After extracting flexibility and agility capabilities from the literature and validating them with U.S. transportation practitioners, the 50 continental state DOTs and Puerto Rico's transportation plans were reviewed to provide standard, emerging and best practice examples for each of the flexibility and agility capabilities. Each state DOT may therefore evaluate how well its long-range transportation plan performs for each flexibility or agility capability and be able to review best practice examples to evaluate for its particular context and implement where appropriate. A detailed description of the development of the tool is available in Garrett (2023).

BROADER CONSIDERATIONS - MEASURING RESILIENCE IN COMPLEX ADAPTIVE SYSTEMS

Complex Adaptive Systems (CAS) are systems made up of many individual parts or agents where there is an “evolving structure”, that is – the systems reorganize their component parts to adapt themselves to problems posed by their surroundings (Carvalhaes et al. 2021). **The transportation system is a complex adaptive system**.

In CAS, observed properties emerge from several interactions among heterogeneous agents. **Resilience is an example of an emergent property of a complex adaptive system.** CAS are difficult to understand and control because they constitute a “moving target” (Holland 1992). Measuring emergent properties, such as resilience, is therefore not an easy task; it is not easy to get it right.

Disaster Resilience Indices (DRI) are a common approach for measuring resilience: temporal snapshots of vulnerability. Particularly popular are composite, quantitative DRI methodologies, geographically mappable. Carvalhaes et al. criticize these approaches as static, reductive and inadequate when viewed under a complexity paradigm. Such approaches may be myopic in terms of complexity. **For DRI, resilience can be misunderstood as anti-vulnerability, and complexity as a multitude of variables**.

Carvalhaes et al. caution that research and development should strive to develop DRI based on the underlying principles of complex adaptive systems. **DRI approaches should therefore consider systemic principles, adopt multi-method, collaborative and Transdisciplinary thinking, top-down quantitative approaches with thick data, network models, and mixed method triangulations**. Mixed methods refer to the appropriate blending of qualitative and quantitative methods.

Such an approach can help researchers develop improved resilience indicators and assessment methods that are clearly differentiated from vulnerability metrics, which should be the aim: **resilience is not defined exclusively as the opposite of vulnerability**. In other words, vulnerability is a necessary but insufficient metric in a broader portfolio of resilience metrics. Using the more holistic approach recommended by Carvalhaes et al. can guide policy and decision makers better, amid future uncertainty, to identify, implement and track capacity-enhancing measures.

The approach taken in this study uses a complex adaptive systems paradigm, coupling vulnerability reduction with resilience capability maturity development, and, including both quantitative and qualitative metrics via multiple lenses to view, track and characterize how well the agency is doing in building resilience. Building resilience involves reducing the vulnerability of its organization and infrastructure system as well as developing a host of resilience capabilities: preparedness, robustness, recovery, capacity to reorganize, adaptive capacity, agility and flexibility, all to enable better handling of all kinds of threats – known, very extreme and unknown; as well as the recognition of opportunities and timely action to secure the most desirable ones.

8 INCORPORATING RESILIENCE CONSIDERATIONS IN PLANNING, TAM AND TSMO

To implement resilience-building strategies effectively, state DOTs can examine and enhance multiple components of the long-range transportation planning (LRTP) process. The Federal Highway Administration has specifically identified the transportation asset management plan (TAMP) and other plans as opportunities to incorporate resilience considerations; their guidance highlights the following areas (FHWA 2018):

1. Incorporate **resilience in the goals and objectives** to guide the plan development.
2. Consider **resilience and reliability when defining the problems and needs** that the plan has to address.
3. Include **resilience considerations in the criteria for evaluating projects**, which are frequently related to performance measures and their targets.
4. Identify, evaluate, and adopt **strategies that will address the identified vulnerabilities** and help achieve resilience goals.
5. Implement **selected strategies to improve resilience**.
6. Monitor, using the pre-selected performance measures, how the strategies are improving resilience to enable **planners to report on the performance to influence their decisions in the update cycle for the plan**.

INCORPORATING FLEXIBILITY/AGILITY IN LONG-RANGE TRANSPORTATION PLANNING

Flexibility and agility are resilience capabilities that can be incorporated into long-range transportation planning practice to enhance an agency's ability to respond effectively in terms of performance, cost and time while adapting their systems and services as needed in the context of disruptions. As transportation agencies must periodically revise their Long-Range Transportation Plans (LRTPs) to provide updates on their transportation system to the Federal government, they are able to evaluate the process to determine areas where they can enhance current approaches to incorporate and enhance flexibility and agility.

For this reason, the *Evaluation Tool for Incorporating Flexibility and Agility into Long-Range Transportation Plans* (also known as the *Flexibility and Agility Scorecards*) was developed and applied to GDOT's 2021 Statewide Strategic Transportation Plan, with specific recommendations to infuse flexibility and agility into the plan and enhance these resilience capabilities in the agency and infrastructure system (Garrett 2023, Garrett et al. 2023c). **Figure 21** maps flexibility and agility dimensions to the steps in the long-range transportation planning process.

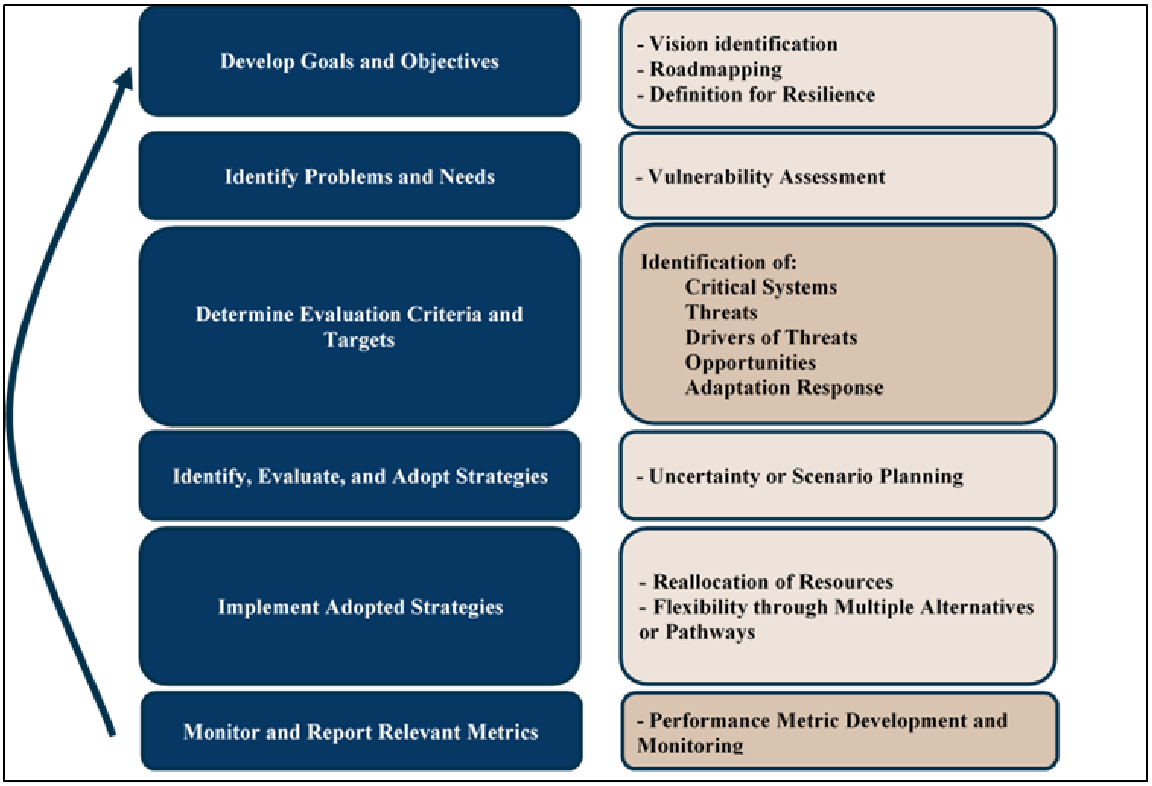


Figure 21. Matrix: Flexibility and Agility Dimensions mapped to the Steps in the Long-Range Transportation Planning Process (Garrett 2023, Garrett et al. 2023)

Development

The *Evaluation Tool for Incorporating Flexibility and Agility into Long-Range Transportation Plans* was developed by identifying capabilities for flexibility and agility in the literature, validating them with transportation practitioners and reviewing and categorizing the 51 long-range transportation plans in the state Departments of Transportation in the U.S. and Puerto Rico in terms of their relative maturity with respect to these validated agility and flexibility capabilities. The scorecards provide effective practices that have already been applied in state DOTs for eight flexibility dimensions and six agility dimensions. Application of these Scorecards therefore facilitates the development of long-range transportation plans that are flexible and agile, and thus enable agencies to enhance their adaptive capacity, become more resilient and develop more resilient systems.

Recommendations for GDOT - integrating Resilience Considerations in LRTP

The list below summarizes the recommendations developed for GDOT based on the findings from the application of the *Evaluation Tool for Flexibility and Agility in Long-*

Range Transportation Planning. These recommendations are to be used as a resource during the next LRTP update, and are presented in the order in which they may be performed in the LRTP development.

Collaboration

- Consider collaboration as an overarching goal for the planning process and for the organization.
- Create task forces to act as community, department, and agency liaisons.

Vision Statement

- Expand the vision statement to explicitly acknowledge uncertainty or resilience.
- Refer to the Federal goas for transportation from 23 CFR § 450.206. Consider how the goals of the LRTP play a role in the other components of the planning process. For example, revising the goals to reflect the current Federal priorities may enable the agency to win funding later in the planning process.

Roadmapping

- Explore both risk-based and resilience-based solutions that are appropriate.
- Throughout the plan, name potential policies that can be implemented at state, regional and local levels to support the achievement of goals and strategies.
- Create teams that enable the agency to develop short-term and medium-term plans to determine how to achieve the described long-term goals and objectives year-by-year.

Defining Resilience

- Review multiple definitions of resilience to find or develop the definition that enables the agency to enact multifaceted solutions for predictable and unpredictable changes as well as general uncertainty. Modify this definition as conditions and needs change.
- State how transportation system performance and resilience are related.

Vulnerability Assessment

- Integrate the outputs of the MHEVRA tool into the goals, strategies, performance measures, targets, and other components of the plan.
- Based on high-risk and high-vulnerability analysis, the agency should make general assessments for next steps to increase the resilience of relevant assets and the system as a whole.

Critical System Identification

- Apply the authentic equity planning framework.
- Apply the MHEVRA Tool to identify critical systems periodically and incorporate the outputs in planning.

Threat Identification

- Identify relevant extreme weather events and potential hazards that may impact the system.
- Identify internal changes to the agency that may threaten the operations or other functions of the organization.
- Note any further external changes that may threaten the transportation system.
- Periodically explore recent research on emerging threats.

Drivers of Threats Identification

- For the threats identified, review potential sources or drivers. For example, if a threat to a transportation system is flooding, potential sources may be sea-level rise, poor drainage, or geographic conditions.
- Describe mitigative actions that can be taken to mitigate threats as well as sources of threats in order to build long-term resilience. Document any mitigative actions taken by the agency that have been successful.

Opportunity Identification

- State implementable actions to build resilience to both predictable and unpredictable changes.
- Review other statewide and regional plans to identify potential opportunities that have not yet been reflected in the state's long-range transportation planning efforts.
- Emerging technologies and research can unveil opportunities for the agency. Periodically review publications and news related to these concepts to illuminate other potential opportunities.
- Consider the distribution of benefits and burdens of the opportunities identified and revise as necessary to promote improved social quality of life for all.

Adaptation Response Identification

- Complete uncertainty and scenario planning efforts and incorporate findings into the plan. Adaptation responses to possible future scenarios can then be identified.
- Review the mitigative actions outlined and search for available opportunities to combine these actions with disaster response and adaptation actions.

- Specifically consider the range of environmental hazards (from recurring storms to catastrophic disasters). Build outlines for adaptation responses to each of these by working with the Georgia Emergency Management Agency (GEMA).
- Identify emergency preparedness of vulnerable communities to understand where there are opportunities to improve community resilience.

Uncertainty or Scenario Planning

- Participate in uncertainty or scenario planning. For reference, utilize examples from other state DOTs (shown in the Flexibility/Agility Tool) to explore and identify contextually-appropriate examples of uncertainty and scenario planning being implemented by other state DOTs.
- Collaborate with consultants to apply the Uncertainty Planning Process Guide developed in this study.
- Consider scenarios beyond funding or investment.

Reallocation of Resources

- Work with GEMA to identify state-owned and maintained assets that could be repurposed or reallocated during an emergency.
- Develop a TSMO plan or work with regional agencies that have developed a TSMO plan to identify resources that could be used flexibly.

Flexibility through Multiple Alternatives or Pathways

- As an agency, reflect on the values that should guide the work of the transportation planning process.
- Use values and dynamically evolving objectives to decide on multiple future alternatives.
- If the outcome or goal is fixed (such as reduced congestion), then consider many potential solutions to integrate increased flexibility into the planning process.

Performance Metric Development and Monitoring

- Based on the goals and strategies of the plan, identify performance metrics to track these initiatives.
- Create routines to track the need to modify these metrics as conditions change.
- Include resilience metrics (including exposure, sensitivity, criticality, adaptive capacity, and others) in the plan.

INCORPORATING RESILIENCE CONSIDERATIONS IN TAM

Transportation asset management plans are required to meet the requirements of Title 23 Code of Federal Regulations (23 CFR) §515 (which defines compliance with 23 USC 119(e)).

The required TAMP **processes** as described by the FHWA are:[2]

1. Process to complete a performance gap analysis and to identify strategies to close gap
2. Process to complete life cycle planning
3. Process to complete a risk analysis and develop a risk management plan
4. Process to develop a financial plan spanning at least a 10-year period
5. Process to develop investment strategies
6. Process for obtaining necessary data from NHS owners other that the State DOT
7. Process for ensuring the TAMP is developed with the best available data and that the State DOT uses bridge and pavement management systems meeting the requirements in the federal legislature to analyze the NHS bridge and pavement conditions

Uncertainty Requirements in TAMPs

The FHWA requires the following of State DOTs in their TAMPs:

- Establish a process for planning for the full **life cycle of assets**, including how to consider "information on current and future environmental conditions including **extreme weather events, climate change, and seismic activity**"
- Establish a process for developing a risk-based management plan, including:
    - Identifying risks from "current and future environmental conditions, such as extreme weather events, climate change, seismic activity, and risks

[2] Federal Highways Administration (2021). Transportation Asset Management Plan Development Processes Certification and Recertification Guidance. Accessed April 24, 2023 from: https://www.fhwa.dot.gov/asset/guidance/certification.pdf

related to recurring damage and costs as identified" in the evaluation of facilities repeatedly damaged by emergency events (discussed above)

- Assessing the **likelihood of risks** and
- **Deciding how risks should be prioritized**
- Developing a mitigation and monitoring approach regarding the highest priority risks
- Summarizing the evaluation of facilities repeatedly damaged by disruptive events

- Include a description of the condition of transportation facilities in the state, which should be influenced by their evaluation of facilities repeatedly damaged by emergency events
- Include a "risk management analysis" related to the evaluation of facilities repeatedly damaged by emergency events
- **Integrate the TAMP into the transportation planning processes used to develop the STIP**

State DOT Experiences Incorporating Uncertainty Considerations in TAMPs

State DOTs have developed a variety of actions to prepare for, respond to, and adapt to external threats and disasters. These actions include the following (Liu & McNeil 2020):

- Developing rapid response plans for external threats as part of the TAMP development process
    - Alabama, Indiana, Kansas, Missouri, Montana, and New York State DOTs
- Risk Assessment
    - California DOT, Delaware DOT
- Coordination and collaboration with other agencies
    - Georgia, Kansas, Minnesota, and New Mexico DOTs
- Mitigation
    - Alaska, Arkansas, California, Delaware, Florida, Georgia, Hawaii, Illinois, Kentucky, Louisiana, Maine, Michigan, Minnesota, Nevada, New York, Ohio, Oklahoma, Oregon, Pennsylvania, Puerto Rico, South Dakota, Texas, Utah, Washington, Wisconsin and Wyoming DOTs
- Most states assess the likelihood of events, prioritize the kinds of risks they would like to prepare for, and include stakeholders in the prioritization process.

Many states have a **risk-based approach** to asset management, which may be deterministic and not enable an agency to practice flexibility in response to emergency events. Adopting a **resilience-based approach** will allow agencies to develop adaptive capacity while encouraging experimentation and learning.[3] **Table 8** below, based on the literature incorporating resilience into TAM, presents opportunities for increased resilience considerations in TAMP.

Table 8. Areas and Opportunities for Resilience Considerations in TAMPs

Area	**Opportunity**
Strategic Goals and Objectives	Revise goals or objectives to address the need to *improve the resilience of Georgia's transportation system* and include a variety of strategies to build transportation system resilience.
Pilot Projects	Identify a pilot project, pilot risk analysis, and test resilience strategies in asset management; report impacts in Transportation Asset Management Plan updates.
Asset Maintenance	Identify opportunities to utilize maintenance projects as retrofit projects to increase adaptability or other options to withstand future high impact events.
Vulnerability Assessment[4]	Consider how assets may be impacted by exposure (climate and weather data), sensitivity (asset condition), and adaptive capacity (redundancy information, simulation, detour impacts).[5]
Community Engagement, Education, and Empowerment[6]	Community resilience can enable lower disaster costs.[7] Supporting community-based resilience approaches can complement the resilience work in the TAMP.
Performance Monitoring	Measure components of vulnerability (exposure, sensitivity, and adaptive capacity) as well as a variety of physical and community resilience metrics. For example, Arizona DOT includes flooding,

[3] Singh,P., Amekudzi-Kennedy, A., and Kassa, H. (2022). Performance Dashboard Tool to Visualize Adaptive Resilience Maturity of Transportation Agencies. *Transportation Research Record*, *2676*(11), 324-339. https://doi.org/10.1177/03611981221092404

[4] Liu, Y., and McNeil, S. (2020). Using Resilience in Risk-Based Asset Management Plans. *Transportation Research Record, 2674*(4), 178-192. https://doi.org/10.1177/0361198120912239

[5] Cuadra et al. (2023). Uncertainty Planning Process Guide. Interactive Power Point Tool. Prepared by Manuel Cuadra. Supported by Georgia Department of Transportation through RP 20-12: Incorporating Resilience Considerations in Transportation Planning, TSMO, and Transportation Asset Management. PI: Adjo Amekudzi-Kennedy, Ph.D., Co-PIs, Baabak Ashuri, Ph.D., Russell Clark, Ph.D., and Brian Woodall, Ph.D., Georgia Institute of Technology, May 2023.

[6] Yang, Y., Nn, S., Xu, F., Skitmore, M., and Zhou, S. (2019). Towards Resilient Civil Infrastructure Asset Management: An Information Elicitation and Analytical Framework. *Sustainability, 11*(16). https://doi.org/10.3390/su11164439

[7] Carvalhaes, T., Chester, M., Reddy, A., and Allenby, B. (2021). An overview & synthesis of disaster resilience indices from a complexity perspective. *International Journal of Disaster Risk Reduction*, *57*. https://doi.org/10.1016/j.ijdrr.2021.102165

	extreme precipitation events, and increasing temperatures in its performance measurement.[8]
Multimodality	Identify and prioritize transportation projects that support multimodality in order to enhance system redundancy, diversity, and reliability.[9]
Project Prioritization and Decision Making	Incorporate climate risk and vulnerability assessments into life cycle and cost-benefit analyses.

TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS (TSMO) PLAN DEVELOPMENT

State DOTs frequently examine the potential to optimize the use of their current infrastructure, processes, technology, and other components of their system in order to improve overall transportation system performance. Some transportation agencies (such as Florida DOT, Iowa DOT, Michigan DOT, Puerto Rico DOT, and others) refer to this as "Transportation Systems Management and Operations" planning, or "TSMO".

The purpose of a TSMO is to generally enhance the performance of the existing transportation system by improving the physical infrastructure as well as the processes, technology, and other system components. TSMO planning can include the following dimensions: business processes, systems and technology, performance measures, culture, organization and workforce, and collaboration.[10] These elements can be evaluated for opportunities to incorporate resilience.

The Federal government has released guidance for state DOTs to develop a TSMO plan and encourages agencies to find agreement on strategic elements (such as goals, performance, and funding components), programmatic elements (such as workforce needs and business processes), and tactical elements (including policies and projects related to TSMO implementation) (FHWA 2017).

Opportunities for TSMO Improvements to Build Resilience

There are a few areas in which state DOTs can incorporate resilience considerations into TSMO planning. The areas are described briefly in **Table 9** below. The strategies

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[8] Arizona DOT. (2020). Asset Management, Extreme Weather, and Proxy Indicators Pilot Project. Arizona Department of Transportation. Accessed April 29, 2023 from: https://azdot.gov/sites/default/files/media/2020/03/ADOT-Asset-Management-Infrastructure-Resilience-Study-Report%20Final-2020.pdf

[9] Carvalhaes, T., Chester, M., Reddy, A., and Allenby, B. (2021). An overview & synthesis of disaster resilience indices from a complexity perspective. *International Journal of Disaster Risk Reduction*, *57*. https://doi.org/10.1016/j.ijdrr.2021.102165

[10] Amekudzi-Kennedy, A., Clark, R., Wilson, J., and Singh, P. (2020). Transportation Performance Management for System Operations: Developments of Processes, Tools, Measures, and Targets. Georgia Tech Research Corporation, Atlanta, GA. Accessed April 27, 2023 from: https://g92018.eos-intl.net/eLibSQL14_G92018_Documents/19-25.pdf

recommended here are practical ways to **reallocate existing resources** to build redundancy by increasing modal options within the existing infrastructure, increase flexibility, or improve agility.

PUBLIC TRANSPORTATION MANAGEMENT*:* Increasing the number of options will increase resilience. As such, utilizing TSMO strategies to improve reliability of public transportation systems, even during extreme events, can provide increased options to transportation systems users.

TRAVEL DEMAND MANAGEMENT: Approaching travel demand as a collection of decisions can enable transportation agencies to increase the flexibility of the implemented solutions.

EVENT MANAGEMENT: Establishing plans for management and operations during special events can help improve the agility by which an agency can act during a disruption to the system.

Table 9. Strategies to Build Resilience and Mitigate Threats Using TSMO[11]

Area	Strategies
Public transportation management	• Transit incentives • Transit lanes • Dynamic transit capacity assignment • Fare strategies • Bus rapid transit • Transfer connection protection • Transit signal priority • Express bus service • Mobility on demand
Travel demand management	• Carpooling/ vanpooling • Telecommuting • Transportation management associations • Dynamic routing • Dynamic ridesharing • Flexible work hours • Bike sharing • Congestion pricing • Mobility-as-a-service
Event management	• Traffic incident management • Planned special event management • Work zone management

[11] Iowa DOT. (2019). Des Moines Metropolitan Area Integrated Corridor Management (ICM): Program-Level Concept of Operations. Accessed April 21, 2023 from: https://iowadot.gov/desmoinesicm/pdf/DesMoines-ICM-ProgramConOps.PDF

	• Weather responsive traffic management • Freight operations and management

Opportunities for Increased Resilience Building in TSMO

Table 10 below is based on the current literature on incorporating resilience into transportation asset management. The areas are presented in three categories of TSMO planning: strategic elements, programmatic elements, and tactical elements.[12] The table summarizes the major opportunities to incorporate resilience into TSMO planning, as identified in the research (Amekudzi et al. 2020; Yang et al. 2019; Zhang et al. 2018; Carvalhaes 2023; Buhl and Markolf 2022) and practitioner (Iowa DOT 2022; North Carolina DOT 2021; Ohio DOT 2020), literature.

Table 10 below presents recommendations for integrating resilience considerations into TSMO planning.

Table 10. Areas and Opportunities to Incorporate Resilience Considerations in TSMO Planning

Area	Opportunity	Sources and References
	Strategic Elements	
Previous Disruptive Events	Determine the impact that extreme events and disruptions on the transportation system and how performance was affected.	Refer to SHELDUS data or use the MHEVRA Tool.
Vision and Program Mission	Identify the overarching TSMO vision for the organization in each relevant program and initiative.	Refer to Iowa DOT TSMO Plan Update.[13]
Strategic Goals and Objectives	Revise goals or objectives to address the need to *improve the resilience of Georgia's transportation system operations and maintenance* that are reflective of existing transportation plans.	Refer to Iowa DOT TSMO Plan Update.[14]
Vulnerability Assessment	Consider how operations may be impacted by exposure (climate and weather data), sensitivity (asset condition), and adaptive	Utilize the MHEVRA Tool and examine the maps for high exposure, high sensitivity, and low adaptive capacity.

[12] Amekudzi-Kennedy, A., Clark, R., Wilson, J., and Singh, P. (2020). Transportation Performance Management for System Operations: Developments of Processes, Tools, Measures, and Targets. Georgia Tech Research Corporation, Atlanta, GA. Accessed April 27, 2023 from: https://g92018.eos-intl.net/eLibSQL14_G92018_Documents/19-25.pdf

[13] Iowa DOT. (2022). Iowa DOT TSMO Plan Update. Accessed April 27, 2023 from: https://iowadot.gov/TSMO/TSMO-Plan-2022.pdf

[14] Iowa DOT. (2022). Iowa DOT TSMO Plan Update. Accessed April 27, 2023 from: https://iowadot.gov/TSMO/TSMO-Plan-2022.pdf

	capacity (redundancy information, simulation, detour impacts).[15]	
Scenario Planning	Utilize scenario planning to explore potential future cases and the variety of possible impacts on operations and maintenance. This enables the agency to identify needs in advance.	Refer to the FHWA's Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance.[16]
Business Case for TSMO Planning	The FHWA recommends referring to case studies and recent costs of extreme weather events to build the business case.	Refer to the FHWA's Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance[17] and Ohio DOT TSMO Study Guidebook: The TSMO B/C Tool. [18]
	Programmatic Elements	
Community Outreach, Engagement, and Empowerment	Supporting community-based resilience approaches can complement the resilience work in the TSMO. [19] Recommended methods include educating and training stakeholders while revising standards to reflect and dynamically evolving infrastructure and community needs.[20]	Refer to North Carolina DOT Resilience Strategy Report.[21]
Resource Needs	Based on the assessment of vulnerability and identified shortcomings, identify where funding, staffing, education, and other resources need to be allocated. Assets can also be examined for opportunities to use existing resources to increase system resilience through reallocation.	Refer to Table 1 for strategies to reallocate existing resources to build resilience using the TSMO.

[15] Cuadra, M. et al. Uncertainty Planning Process Guide. Interactive Power Point Tool. Prepared by Manuel Cuadra. Supported by Georgia Department of Transportation through RP 20-12: Incorporating Resilience Considerations in Transportation Planning, TSMO, and Transportation Asset Management. PI: Adjo Amekudzi-Kennedy, Ph.D., Co-PIs, Baabak Ashuri, Ph.D., Russell Clark, Ph.D., and Brian Woodall, Ph.D., Georgia Institute of Technology, May 2023.
[16] USDOT FHWA. (2015). Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance. Accessed April 29, 2023 from: https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf
[17] USDOT FHWA. (2015). Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance. Accessed April 29, 2023 from: https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf
[18] Ohio DOT. (2020). Transportation Systems Management & Operations Study Guidebook. Prepared by Gannett Fleming. Accessed August 22, 2023 from: https://www.transportation.ohio.gov/programs/tsmo/resources/tsmo-guidebook
[19] Yang, Y., Nn, S., Xu, F., Skitmore, M., and Zhou, S. (2019). Towards Resilient Civil Infrastructure Asset Management: An Information Elicitation and Analytical Framework. *Sustainability*, *11*(16). https://doi.org/10.3390/su11164439
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[21] North Carolina Department of Transportation (2021). NCDOT Resilience Strategy Report. Accessed April 13, 2023 from: https://files.nc.gov/ncdeq/climate-change/resilience-plan/agency-reports/Department-of-Transportation-2021-Resilient-Strategy-Report.pdf

Tactical Elements		
Emergency Rapid Response Plans	Utilizing the communication efforts and Vulnerability Assessment, identify rapid response plans in the case of an emergency. TSMO planning can incorporate elements of emergency transportation operations planning in a variety of areas (including the use of ITS).	Refer to the Iowa DOT TSMO Plan Update.[22]
Pilot Project	Investigate and identify a high impact corridor that could be used as a pilot project for TSMO planning methodologies that incorporate resilience strategies.	Refer to North Carolina DOT Resilience Strategy Report.[23]
Multimodality	Identify and prioritize transportation projects that support multimodality in order to enhance system options, redundancy, and reliability.	Refer to North Carolina DOT Resilience Strategy Report.[24]
Performance Monitoring and Assessment	Create and monitor performance metrics related to TSMO, maintenance, and emergency management. Implement both targets to track progress and thresholds to determine when certain resilience-related actions (e.g., resource and budget reallocation, emergency plan implementation) should be implemented.	Refer to the Iowa DOT TSMO Plan Update.[25]
Project Prioritization and Decision-Making	Include TSMO priorities within decision-making. Multi-criteria decision making and decision making under (deep) uncertainty (DMDU) approaches can be integrated with lifecycle analysis to find which alternatives are more sustainable and resilient in various future scenarios.[26]	Refer to Ohio DOT TSMO Study Guidebook: The TSMO B/C Tool.[27]

[22] Iowa DOT. (2022). Iowa DOT TSMO Plan Update. Accessed April 27, 2023 from: https://iowadot.gov/TSMO/TSMO-Plan-2022.pdf

[23] North Carolina Department of Transportation (2021). NCDOT Resilience Strategy Report. Accessed April 13, 2023 from: https://files.nc.gov/ncdeq/climate-change/resilience-plan/agency-reports/Department-of-Transportation-2021-Resilient-Strategy-Report.pdf

[24] North Carolina Department of Transportation (2021). NCDOT Resilience Strategy Report. Accessed April 13, 2023 from: https://files.nc.gov/ncdeq/climate-change/resilience-plan/agency-reports/Department-of-Transportation-2021-Resilient-Strategy-Report.pdf

[25] Iowa DOT. (2022). Iowa DOT TSMO Plan Update. Accessed April 27, 2023 from: https://iowadot.gov/TSMO/TSMO-Plan-2022.pdf

[26] Buhl, M., and Markolf, S. (2022). A review of emerging strategies for incorporating climate change considerations into infrastructure planning, design, and decision making. *Sustainable and Resilient Infrastructure, 8(1)*, 157-169. https://doi.org/10.1080/23789689.2022.2134646

[27] Ohio DOT. (2020). Transportation Systems Management & Operations Study Guidebook. Prepared by Gannett Fleming. Accessed August 22, 2023 from: https://www.transportation.ohio.gov/programs/tsmo/resources/tsmo-guidebook

9 PLANNING AND PROJECT EVALUATION UNDER DEEP UNCERTAINTY: A PROCESS GUIDE

Uncertainty planning is an essential component of resilience planning because not all threats can be anticipated and quantified as risks. The study developed a framework for Uncertainty Planning (Cuadra 2023, Cuadra et al. 2023) to address those situations where it is difficult to anticipate threats or the threats remain unknown, e.g., Few organizations, if any, planned for COVID-19. The Guide, in the form of an interactive PowerPoint Tool, aims to promote greater transportation resilience under a wide variety of conditions. Anticipated benefits include better reliability in the infrastructure system, reduced operation recovery costs, and new opportunities for operational improvements, if the agency monitors conditions as per the recommendations.

The framework is presented as three components, with guidance for different department programs to apply the tool. These components are intended to be used together as shown below in **Figure 22**. The three components are meant to inform and realign one another. A **Top-Down approach** is recommended for the state DOT headquarters (central office) and strategic planning, and infrastructure development. A **Bottom-Up approach** is recommended for TAMP strategy, STIP and TIP prioritization, and verification of the feasibility of the strategic plan. Finally, a **Project-Level approach** is recommended for individual asset replacement and modification, as well as single-asset capital outlays.

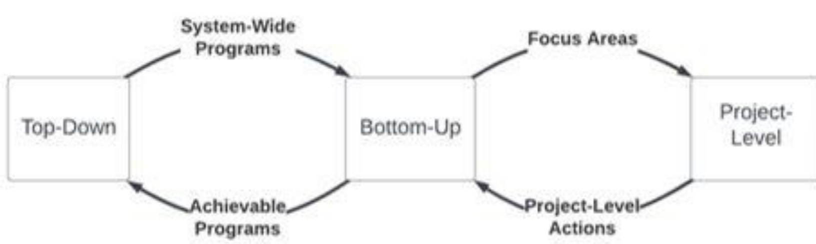

Figure 22. Diagram: Informing Relationship among the Three Components of Uncertainty Planning (Cuadra 2023, Cuadra et al. 2023)

THE TOP-DOWN APPROACH

The Top-Down approach addresses deep uncertainty directly, through decision-making science and resilient asset management. Deep uncertainty is especially difficult to handle, as it involves uncertainty in system and asset behavior, and stakeholder needs, as well as environmental variability. In response, the Top-Down approach asks questions to reduce unknowns and define the problem. In particular, it determines which factors are most uncertain and which are most important to infrastructure performance. Then, the approach selects an overall strategy, ranging from planning projects that survive most possible scenarios, to incremental project planning that survives continuously updated conditions.

The approach then recommends testing alternatives and preparing to support chosen projects with further actions to manage conditions. These actions include *Proactive Actions* to guide the system through condition variability, *Bracing Actions* to prepare for major changes, and *Reactive Actions* to correct conditions and seize opportunities. The approach then recommends indicators to monitor system vulnerability. Exposure, sensitivity, adaptive capacity and criticality are recommended indicators to enable the most vulnerable and mission-critical assets to be prioritized for resilience management.

THE BOTTOM-UP APPROACH

The Bottom-Up Approach is meant to complement the Top-Down Approach, and to emphasize the importance of meeting the constituent communities' goals. Regional and local agencies must meet their development goals as must the central office: The Bottom-Up approach deliberately plans local resilience and aggregates actions in to programs for state implementation. Emphasis on local goals also helps verify that the Top-Down approach goals are compatible with the needs of constituent agencies.

The approach first recommends that agencies record, organize, and consult asset deterioration causes, modes, and costs so that hazard conditions can be determined. In parallel, records of adaptation project frequency, cost, and performance can be consulted to identify effective adaptation practice. Experimentation, standardization, and eventually mass reproducibility of common adaptations is recommended so that adaptive actions can be quickly and efficiently implemented when necessary.

The approach also recommends GIS tools to map emerging critical conditions, and to anticipate resilience needs on the horizon. Finally, the approach recommends overall strategies for different users and purposes. Long-term, programmatic strategies are recommended for central offices, while resource-constrained strategies are recommended for offices whose objectives follow state initiatives.

THE PROJECT-LEVEL APPROACH

The Project-Level Approach is proposed for uncertainties that assets face largely on an individual scale. The approach is necessary, as resilient infrastructure requires individually resilient projects and assets. Also, constructed assets need additional flexibility planning for dynamic management compared to large systems that are not yet fully constructed.

The approach begins by asking some of the same questions as the Top-Down Approach to determine the most uncertain and most important factors. The approach then models project alternatives to identify critical factors and events affecting performance. Using this information, the approach identifies tradeoffs and advantageous conditions for alternatives, to make conditional decisions.

Finally, the approach recommends supporting actions based on the identified advantageous and disadvantageous conditions for the alternatives, and for scenarios that could not be modeled directly. In cases with enough resources for modeling, the approach recommends modeling supporting actions as well.

Case Study: The Talmadge Memorial Bridge

The Project-Level Approach was demonstrated using the Talmadge Memorial Bridge replacement as a case study. Three alternatives - a high, single bridge, a higher two-deck bridge, and a tunnel - were all modeled noting that the provision of a reliable road link and access to the Port of Savannah was most important. A simulation was then used to model the lifecycles of each of the three alternatives, tracking lifetime costs and major adaptations as major and uncertain factors varied. The results of the case study simulation are shown in **Figure 23** below. Considering the large differences in lifecycle cost, it was determined that only in cases of slow population growth should the tunnel be chosen, and, otherwise, the double bridge was least likely to need major adaption due to its higher deck at the beginning of the project lifecycle. A simple matrix of recommendations based on the conditions is shown in **Figure 20**.

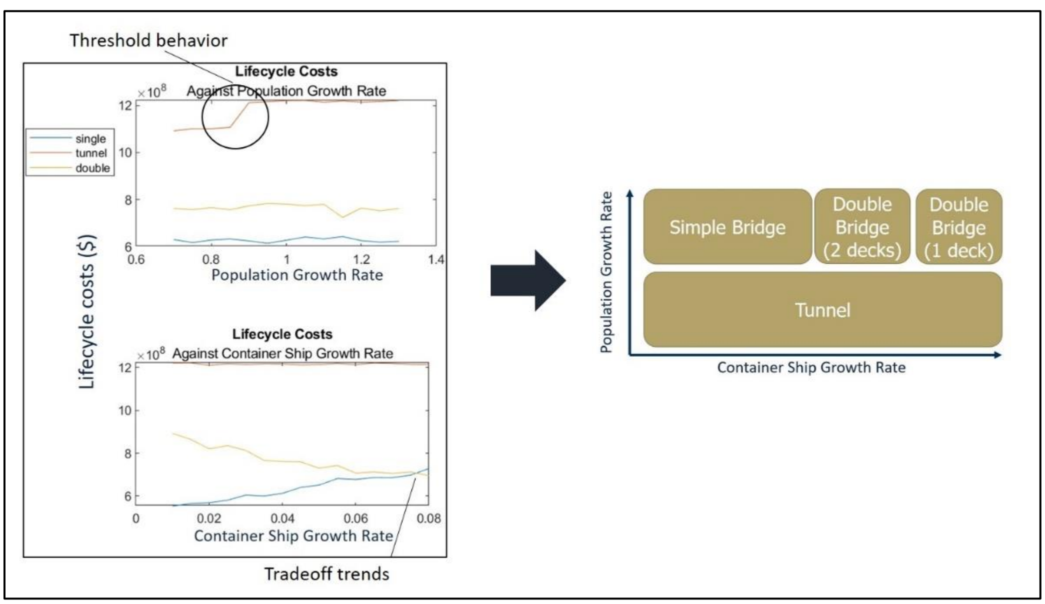

Figure 23. Diagram: Lifecycle Costs of Modeled Case-Study Alternatives with Recommendations (Cuadra 2023, Cuadra et al. 2023)

The case study then recommended supporting actions to promote advantageous environmental and operational conditions for any of the three alternatives. This case study incorporated both climate and demand factors in the modeling, but noted that because of limited documentation of climate stresses, the results were dominated by demand and operational factors.

Uncertainty Planning is recommended for consultant application in collaboration with state engineers because several of the recommended procedures do not have defined standards compatible with required state practice. Additionally, due to the long planning timeline, some recommended practices require emerging technology and practices that are not yet standardized with best practices. Thus, it was difficult to find illustrative examples.

Finally, since deep uncertainty and resilience planning are both usually very context-dependent exercises, planning and design guidelines will be useful future work for agency research and development. The framework provides recommendations that can be applied to various contexts by consulting experts, and is expected to yield benefits. In particular, application of this framework is expected to improve state asset inventory condition and state preparedness for future uncertainty.

State preparedness includes both protection from disaster and preparedness to seize opportunities. If the agency plans respond to hazards and monitor threats, they can save lives and resources in disaster situations. Similarly, if the agency records discretionary projects and looks for signs of opportunity, it can implement more projects with desirable returns to system performance.

CLIMATE HAZARDS AND SENSOR MONITORING SOLUTIONS

Sensor technologies have a wide range of applications in monitoring transportation infrastructure for the impact from hazards on functionality and operation. Carefully selected monitoring applications can augment resilience planning and cost-effectiveness.

To address the limits on how much of the system can be adapted at once, some critical assets and corridors may be candidates for monitoring. Also, the most critical assets in emerging hotspot areas for particular hazards may be prioritized for monitoring. Continued monitoring of this subset of critical assets and corridors will enable agencies to develop dynamic/adaptive/robust data-driven plans to provide guidance on appropriate future actions as conditions continue to change. By developing such plans, an agency can manage these corridors dynamically.

This study conducted a pilot on bridge scour on the coast of Georgia to evaluate new low-cost monitoring approaches and highlight the value that effective monitoring in resilience planning and performance management. Bridge scour is commonly caused by fastmoving water that washes away the foundations around bridge supports, compromising the bridge structure. The team identified a bridge on the Georgia coast for the evaluation of sensor technologies. This location includes a typical concrete piling structure built over a sandy soil mix in an area that experiences significant tidal flow. Regular changes to the riverbed can be observed at low tide after storm events.

Table 10 provides a summary of the solutions evaluated for their feasibility during this study. There are several promising approaches for low-cost monitoring of bridge scour for the agency to consider.

Table 10. Scour Monitoring Solutions

Solution	Study Results
Underwater sonar	Several commercial offerings were evaluated such as Fondriest Environmental. These are not included in the current pilot installation due to the high cost around $10,000 each. The team will continue to pursue lower cost sonar units for this solution. This is the most feasible approach if the bridge location does not regularly experience a dry river bed.
Ultrasonic water and ground level	Deployed widely for water level monitoring at less than $1000 each. (sealevelsensors.org) These can also detect changes in ground level during dry periods. The recommended deployment is to install one sensor at each pier section.
Digital camera with human inspector	A common approach is to install a remote camera that allows inspectors to review the bridge footings remotely. This requires a high speed data link that increases the cost of operation as well as the regular inspector time.
Digital camera with automated inspection	This project is experimenting with AI/ML techniques to automatically detect water level and water flow rates. These installations can also be used for detecting changes in the river bed during dry periods. Early results are promising and the team will continue this pursuit.
Digital camera with automated vehicle counting	Uses image processing to count and classify vehicles on a roadway. The team is using systems from Telraam (telraam.net) that are available for less than $400. These are useful

	in verifying traffic counts to correlate with other bridge structural data.
Vibration detection	This approach monitors vibration patterns in the bridge structure to identify changes that might indicate a structural compromise. There are several prior research efforts utilizing integrated monitoring. This study is testing the Raspberry Shake seismograph (raspberryshake.org) available for less than $1,000. The units show promise for detecting different vehicle types. Longer term study is needed to assess the potential for detecting structural changes.

10 Conclusion

Developing a robust resilience building strategy and capabilities is increasingly critical to a highly performing transportation system and other systems (interdependent and otherwise) as climate and other disruptions continue to threaten and affect transportation performance. The RP 20-12 project: *Incorporating Resilience Considerations in Transportation Planning, TSMO and Asset Management*, has developed a robust risk-based and adaptive resilience approach that offers the data, analytical and planning resources to identify, characterize and reduce asset and infrastructure system vulnerabilities, and simultaneously build a range of resilience capabilities in the organization and infrastructure system to manage uncertainties that are less known (i.e., very extreme events) or unknown. Rather than being a one-and-done activity, resilience building is an integral part of performance management and must be integrated well into an agency's business processes – including visioning and strategic planning, long-range transportation planning, system management and operations, asset management, project development and prioritization, and other key elements of the agency's processes. The RP 20-12 project has provided a suite of decision-support tools to enable the agency to approach its business with a resilience lens. Future work must include developing the necessary capabilities to ensure that resilience is developed appropriately in underserved communities; incorporating downscaled climate projection data for considerations of the changing climate based on both past and future data; and, conducting simulation and modeling to enhance network redundancy.

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