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SCOPING STUDY TO DEVELOP THE BASIS FOR A HIGHWAY STANDARD TO CONDUCT AN ALL-HAZARDS RISK AND RESILIENCE ANALYSIS

DRAFT FINAL PROJECT REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
of
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EXECUTIVE SUMMARY

Transportation owners and operators are responsible for the Highway System and the delivery of a range of services and functions through the management of that system. There are inherent risks involved with the management of these systems, notwithstanding aging infrastructure, and fiscally constrained resources. Many agencies are moving toward performance-based resource allocation while simultaneously recognizing risks that may undermine their strategic goals. As these risks affect every component of a highway system to a greater or lesser extent, accurately accounting for and addressing these risks within a highway agency's enterprise-wide management program is the goal that currently lacks analysis tools.

Investing in risk and resilience strategies and enhanced recovery to reduce or eliminate the impact of external events is also paramount to ensure a thriving, viable transportation system. Risk management requires the identification and assessment of potential threats and hazards and vulnerabilities, the evaluation of potential mitigation actions to reduce risk, clear and easy implementation of a process to prioritize mitigation activities, and investment that aligns with agency strategic and performance goals. Asset management, and more recently performance management, has been an ongoing focus of many research efforts.

In addition, transportation agencies currently have to meet federal regulations that require the incorporation of risk and resilience into their activities including MAP-21, FHWA 5520, and more recently the Infrastructure Investment and Jobs Act (IIJA). However, guidance for analytical risk assessment methods to support risk-based processes is lagging. Risk assessment processes, methods, and tools are needed to integrate risk management into asset and performance management systems as well as a clear understanding of the relationship between risks and system resilience.

This research provides an understanding of the research required to establish quantitative methods to support all-hazards risk and resilience analysis for the highway system. In completing Phase I of the project, the research team performed an extensive literature of domestic and international sources, developed a glossary of terms, particularly for risk and resilience (R&R) of highway assets, and conducted a gap assessment of the state of practice on the topic.

The glossary of terms was developed using the quantitative risk and resilience assessment for highway infrastructure and contained 213 words with definitions drawn from 91 sources. The literature review includes an overview of the different R&R policies, definitions, frameworks, metrics, assessment methodologies, and tools currently used domestically and internationally. The glossary of terms was developed using the quantitative risk and resilience assessment for highway infrastructure and contained 213 words with definitions drawn from 91 sources.

Utilizing the findings from the literature review, the research team conducted a gap analysis started with the barriers, limitations, successes, and lessons learned. The potential gaps were compiled and organized into three categories: *Processes, Technologies and Tools, and Technical*

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Capacity Building. These gaps were further validated in two industry engagements and served as the basis to create the three thematic lanes for the research roadmap and identify the necessary topics for future research.

Phase II of the research project focused on developing an R&R framework, a research roadmap, and associated research problem statements for the development and implementation of a quantitative risk and resilience manual for highway assets.

The R&R framework was developed after studying multiple R&R frameworks during the literature review phase. The R&R framework builds up from the most comprehensive and used frameworks including the AASHTO's framework from the Transportation Management Guide to incorporate risk management into Transportation Management Plans (TAMPs), the FHWA Vulnerability Assessment and Adaptation Framework, the risk management framework from the International Organization of Standardization ISO 31000 and the Risk Analysis and Management for Critical Asset Protection (RAMCAP Plus™) framework among others. The enhanced framework consists of four modules: (*1) Organization, (2) Scoping, (3) Assessment, and 4) Management.* Each one of these modules has particular steps that need to be accomplished.

The research team developed the research roadmap using the findings from Phase I and the R&R framework. The roadmap has three thematic lanes identified in the gap assessments and has a total duration of seven years with three defined phases and products for each phase. **Phase 1** (3-year duration) of the research roadmap focuses on the development of the "Highway Risk & Resilience (R&R) Manual", **Phase 2** (2-year duration) focuses on pilot testing and implementation of the "Highway Risk & Resilience (R&R) Manual", and **Phase 3** (3-year duration) focuses on the development of tools and revision of the "Highway Risk & Resilience (R&R) Manual". Each one of these phases has different topics and proposed projects associated with them. The research team proposed a total of 12 research problem statements (RPSs) to accomplish the development and implementation of the "Highway Risk & Resilience (R&R) Manual" and tools. The roadmap and RPSs were validated during a stakeholder engagement and by further interactions with the technical panel.

In addition to the glossary of terms, literature review report, gap assessment report, the R&R framework, research roadmap, and the research problem statements, the research team also developed an implementation technical memorandum and communication material including a fact sheet/flyer and a set of presentation slides summarizing the project.

The work developed for NCHRP 23-09 identified the key areas that need the most attention for the development of quantitative risk and resilience for highways methodologies and tools and steps for successful implementation within transportation agencies.

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1. INTRODUCTION

This document details the research conducted for National Cooperative Highway Research Program (NCHRP) Project 23-09: *Scoping Study to Develop the Basis for a Highway Framework to Conduct an All-Hazards Risk and Resilience Analysis.* This report contains findings from the two phases of the project.

Phase I involved the following activities:

- Developing a robust risk and resilience glossary of terms
- Gathering information through a comprehensive literature review
- Identification of high-priority gaps in the state of practice
- Engagement in the transportation industry to validate gaps and obtain information for roadmap development
- Development of multiple drafts/high-level roadmap

approaches Phase II involved the following activities:

- Draft research roadmap options.
- Engage the transportation industry to review proposed roadmap options.
- Develop research problem statements
- Develop implementation memorandum
- Develop communication material

1.1. Background

Recent research has revealed how agencies differ in the ways they incorporate risk and resilience analysis into their planning process-- in the methodologies, they employ (quantitative versus qualitative), the quality of available data, the selection of metrics, the availability and use of tools, and even their understanding of what risk and resilience are and how they relate to each other.

In 2014 the FHWA published Executive Order 5520, encouraging state DOTs, MPOs, and local and tribal agencies to develop strategies to minimize extreme weather and climate change risks and to use the best science and technology available to protect critical infrastructure. In response, transportation agencies drafted risk-based asset management plans and performance-based metrics to assist in planning and prioritizing investments. Nevertheless, transportation professionals have expressed a need for guidance on risk and resilience assessment methodologies, metrics, and tools. More recently, on November 15th, 2021, President Biden signed the $1 Trillion Infrastructure Investment and Jobs Act (IIJA), also known as Bipartisan Infrastructure Law (BIL). The IIJA/BIL authorizes about $47 billion for resilience and climate-related programs. Part of the requirements of IIJA includes establishing a risk and system resilience assessment intergovernmental process. Based on this, "USDOT will be

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required to work with federal, state, and local agencies to develop a process for quantifying annual risk to increase system resilience within the nation's surface transportation system. USDOT will be instructed to provide guidance and technical assistance to state and local agencies on the process."[1] BIL authorizes funding for resilience and climate-related programs to address flood mitigation, cyber, waste management, flood and wildfire mitigation, drought, and coastal resiliency, ecosystem restoration, heat stress, and weatherization. Further, the bill creates a new Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation (PROTECT) grant program. This program establishes a formula and competitive grant program to help States improve the resiliency of their transportation systems. Specifically, PROTECT grants will "will support planning, resilience improvements, community resilience and evacuation routes, and at-risk coastal infrastructure" [1]. Some specific provisions of BIL applicable to the highway sector include:

- National Highway Performance Program (NHPP) includes funding for resilience improvements for the National Highway System (NHS), including protective features to mitigate cyber risk to the NHS and protective features to mitigate the risk of recurring damage or future repairs from extreme weather, flooding, or other disasters.
- Requires consideration of extreme weather and resilience in lifecycle cost and risk management analysis.
- Equity: restore community connectivity by removing, retrofitting, or mitigating highways or other facilities that crate barriers to community connectivity.
- The language for ER funding has been expanded to include wildfire as an eligible disaster and economically justifiable improvements intended to mitigate the risk of recurring damage from extreme weather, flooding, and other natural disasters.

NCHRP 23-09 comes at an opportune time while the nation is focused on meeting federal requirements and a growing portfolio of emerging threats. The need to improve system resilience from extreme weather events and climate change is called out in FHWA Executive Order 5520. In addition to extreme weather and climate change, transportation agencies encounter a large variety of risks including natural hazards (e.g., flooding, ice storms, climate change, etc.), biological threats (e.g., pandemic), cyber-attacks, dependency on other infrastructure types (e.g., electricity, communications, and water systems), physical attacks (e.g., terrorism), funding uncertainty, asset deterioration, and aging, regulatory changes, and political threats among others. NCHRP 23-09 will set the ground for the development of a standardized process to meet these requirements.

1.2. Research Objectives

The primary objectives of the NCHRP 23-09 Project, *Scoping Study to Develop the Basis for a Highway Framework to Conduct an All-Hazards Risk and Resilience Analysis*, are to (1) develop a

[1] https://www.naco.org/resources/legislative-analysis-counties-infrastructure-investment-jobs-act

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A comprehensive and consistent set of risk and resilience related terminology and (2) formulate a research roadmap to establish a framework that supports quantitative all-hazard risk and resilience assessments for state and local departments of transportation. The NCHRP 23-09 research project in its execution, will facilitate the communication of ideas garnered through literature review, surveys, and subject matter expert feedback.

1.3. Organization of Report

This final report is organized as follows:

Chapter 1. Introduction – This chapter introduces the report's background, objectives, and overview.

Chapter 2. State of Practice Review – This chapter presents a comprehensive glossary of terms related to risk and resilience for highway infrastructure, an overview of the risk and resilience definitions, policies, frameworks, assessment methodologies, management, and data needs, a gap assessment, and a stakeholder engagement to validate state of practice.

Chapter 3. Risk and Resilience Framework – This chapter presents a comprehensive framework for conducting risk and resilience assessment and management.

Chapter 4. Roadmap – This chapter provides the proposed research roadmap for developing and implementing a quantitative risk and resilience assessment manual for highway assets.

Chapter 5. Research Problem Statements – This chapter presents the detailed research problem statements (RPSs) corresponding to the proposed research roadmap.

Chapter 6. Stakeholder Engagement (Industry Workshop II) – This chapter presents an overview of a stakeholder engagement to obtain feedback on the proposed research roadmap and problem statements.

Chapter 7. Research Outputs and Next Steps – This chapter lists and briefly describes all other documentation created as part of the research effort, including communication material and the implementation technical memorandum.

Chapter 8. Conclusions of Research – This chapter summarizes the key findings based on the literature review, gap assessment, and industry workshops.

Appendices – Included here are the complete glossary of terms, literature review, gap assessment, workshops summaries, research problem statements, communication material, and implementation memorandum.

2. STATE OF PRACTICE REVIEW

Phase I of the research involved the development of a comprehensive glossary of terms related to risk and resilience, a comprehensive literature review, a gap assessment of the state of practice, and the development of multiple draft approaches for roadmap development. This

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chapter of the report describes the approaches used by the research team for each of these activities.

2.1. Glossary of Terms

The first step in this research was to develop a glossary of terms. Many different glossaries of terms related to risk and resilience have been developed in multiple sectors and from different perspectives. (e.g., cyber-risk versus climate change resilience). The glossary of terms developed in this project was developed with the lens of quantitative all-hazards risk and resilience analysis for highway infrastructure. The glossary intended to coalesce the language surrounding all-hazards risk and resilience and to bring together the multiple authoritative definitions for review as an industry. The intent was to evolve this glossary to reduce confusion and increase clarity toward a comprehensive and consistent set of risk-and-resilience-related terminology for transportation agency use. The current glossary contains 213 words with definitions drawn from 91 sources.

Definitions were derived to the extent possible from sources published by the transportation sector, such as the Federal Highway Administration (FHWA) Planning Glossary, the TRB Glossary, various NCHRP reports, and the American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management (TAM) Guide. Some definitions are based on the Federal Emergency Management Administration (FEMA) language. Additionally, certain definitions are derived from glossaries contained in the American Society of Mechanical Engineers (ASME) Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus manual and the American Water Works Association (AWWA) J100 standard. Multiple definitions are included in this glossary to provide context and to help transportation professionals understand the nuance and contextual differences among authoritative sources.

After a draft version of the glossary of terms was submitted and reviewed by the panel, a revised version was developed addressing all panel comments to the best of the team's ability.

Appendix A of this document includes the glossary of terms and includes a single table listing all 213 terms, followed by each term with accompanying definition and source attribution in alphabetical order.

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2.2. Literature Review

In conducting the literature review, the research team assembled an extensive inventory of existing research, tools, and key products that are relevant to this project. In addition, the research team looks at national and international sources for identifying best practice guidance and risk and resilience assessment methodologies. In all, the team reviewed well over 230 active and past research reports where risk and resilience were discussed or employed in the context of highway asset analysis. This list included general research reports, state asset management plans, guidelines, state performance reports, management tool application documents, and state policies and recommendations. While transportation is the central focus of this project, literature from other relevant fields was included for added insight. The search included:

- Traditional academic journal databases via Google Scholar
- TRB's integrated database, TRID
- AASHTO's TAM Portal
- Review of U.S DOT website, as well as state DOT websites and publications
- Materials suggested by resiliency and risk management experts at each firm.

The research team briefly reviewed the list of 230 documents, with summary comments on the document relevance included in a table of resources. The resource review was organized by section in a shared excel document to add input for the whole research team. This allowed easy access and comprehension of the various topics covered in the following literature review. Each resource had a link to access the complete publication, the type, and date of publication, comments relating to the document, and the contributing research team member's name. The review format allowed the team to pull the necessary resources quickly and efficiently when producing the review itself. From this list of 230 documents, 219 documents were deemed relevant and helpful. These formed the basis of the literature review.

The research team made the following key observations about the findings in the literature review:

- In many cases, risk and resilience concepts are used interchangeably among state and local DOTs. There is a need for education to help transportation professionals understand how these two terms relate and the relevant metrics for each term.
- It has been observed that many metrics for resilience incorporate risk measures. There is an inverse relationship between risk and resilience where reducing risk increases resilience and vice versa. However, other factors such as planning for a response, recovery, and adaptation play a significant role in system resilience.

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- There are minimal differences in AASHTO and FHWA definitions for risk and resilience. Many states have adopted either the FHWA or AASHTO risk and resilience definitions. However, some states have developed their definitions.
- Most states are currently performing risk assessments by using simple risk registers based on a five-point rating that relies on a collective judgment. A few state DOTs are expanding their initiatives and incorporating quantitative methodologies for risk and resilience assessments.
- Multiple federal transportation agencies, state DOTs, and Metropolitan Planning Organizations (MPOs) have performed vulnerability assessments using the FHWA Vulnerability Assessment and Adaptation Framework (VAAF) or a variation of it during FHWA sponsored resilience pilot projects.
- There is no standard methodology for performing quantitative risk and resilience assessments for transportation agencies; however, other sectors such as the water/wastewater industry and the energy industry have developed methodologies that are more widely adopted and applied in their industries.

Appendix B of this report presents the developed literature review for this project.

2.3. Gap Assessment

Exploiting the findings of the literature review, the research team conducted a gap assessment to identify gaps existing in the state of practice of how state DOTs conduct quantitative all-hazard risk and resilience assessments.

The methodology for the gap analysis started with the barriers and limitations that were noted in the state of practice report. That information was reviewed in detail, including the limitations and lessons learned. Potential gaps were compiled and organized into three categories:

1. ***Processes***

This set of gaps relates to the business processes for state DOTs, Emergency Management Agencies (EMAs), and other partner organizations. Various methods and frameworks have been adopted to conduct risk and resilience assessments with varying levels of analytical or evaluation effort covering both qualitative and quantitative approaches. The major gaps identified in this category include:

- Risk and resilience assessment to support interagency planning for disasters
- Defining and adopting risk and resilience performance measures
- Monitoring results of risk and resilience assessments and their integration into DOT decision-making
- Scoping guidance for risk and resilience analysis

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2. ***Technologies and Tools***

The second set of gaps relates to the technologies and tools that are used to support risk and resilience assessments. As listed in the literature review, there are a variety of technologies and tools that are available to planners. These include:

- Qualitative, semiquantitative, and quantitative risk assessment tools
- Asset vulnerability estimation tools and
- Criticality and communication tools

These tools have limitations and gaps in their underlying methodologies and data requirements necessary for their use. The main identified gaps for this section are:

- Choice of methodology for risk and resilience assessment tools (e.g., qualitative, quantitative, deterministic, probabilistic, etc.)
- Data availability and suitability for risk and resilience assessments
- Developed standard consequence estimation methodologies

3. ***Technical Capacity Building***

The final set of gaps relates to agencies' technical capacity to carry out risk and resilience assessments. As risk and resilience methodologies become more sophisticated, they require more staff training and additional skill development to regularly conduct assessments within constrained resources. The gaps cataloged here document the challenges agencies face in building capacity to handle increasing technical demands.

- Training material available for DOT staff for risk and resilience assessments
- Variety of definitions and frameworks for risk and resilience analyses
- Many risks and resilience tools do not meet accessibility principles and standards

The detailed gap assessment for this project is presented in Appendix C of this report. These gaps were further validated during two different industry workshops.

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2.4. Stakeholder Engagement I (Industry Workshops)

The research team conducted two interactive stakeholder engagements (Industry Workshops) with representation from state DOTs staff, local agencies, academia, and private consultants. Over 21 States were represented between the two workshops with participants from different areas and levels of state DOTs, US DOT, AASHTO, FHWA, local agencies, academia, and the private sector. Figure 2-1 shows the geographical distribution of participants.

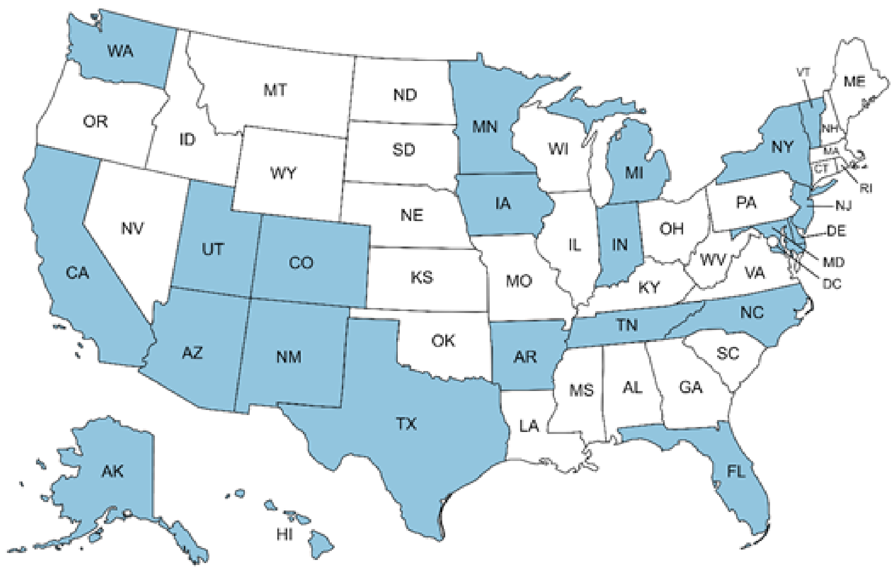

Figure 2-1. Industry Workshop Geographical Distribution of Participants

These workshops were an important factor to ensure a standardized process to conduct an all-hazards risk and resilience analysis of highway assets would meet the transportation industry's needs. This workshop helped the research team to:

- Validate gaps identified in the state of practice
- Obtain information for the development of the risk and resilience framework and roadmap
- Identify working groups to validate the roadmap and research problem statements

The workshops consisted primarily of participant responses to a series of searching questions, as well as an open discussion on deep-dive topics, and was conducted using online platforms and tools (Zoom for the discussion and Mentimeter for questions). Break-out groups were created based on information provided on the registration site regarding affiliation (e.g. state DOT) area of expertise (e.g. asset management) and location (e.g. east coast). Participation and attendance during the 3-hour workshops were very successful with the March Workshop having 21 participants and the April Workshop having 34.

During the Workshop several key points were emphasized and raised consistently by participants across topics:

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- The need for resources and tools that are easy to use and understand allows agencies to better perform in-house assessments.
- The need for updated guidance and education for staff and leadership including training to assist staff in conducting risk and resilience analysis.
- The need for a clear and defined definition of risk and resilience.
- Utilizing a combination approach of deterministic and probabilistic quantitative factors when creating the risk and resilience framework.
- Address gaps in agencies' missing functionality and confusion on the "right" tool to use when working on risk and resilience initiatives.
- Future development on the use of economic analyses for alternative resilience improvements within agencies and incorporating risk and resilience assessments into decision-making.

Overall, workshop participants concurred with the findings from the gap assessment. In addition, participants emphasized a need for tools that are easy to use, require minimum data inputs, and produce outputs meaningful to decision-makers.

In addition, information to better inform the research roadmap and risk and resilience (R&R) manual was gathered through a series of questions introduced to participants during the workshop. Some of the questions included:

- Identification of most significant threats and assets to include in the R&R manual
- Type of analysis to be included in the R&R manual (deterministic versus probabilistic)
- Metrics to be developed for both risk and resilience
- The best way to promote the adoption of the R&R manual once established
- Use of the R&R manual (e.g., project prioritization)

A technical memorandum summarizing the outcomes from both industry workshops is provided in Appendix E of this report.

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3. RISK AND RESILIENCE FRAMEWORK

To successfully integrate risk and resilience into all facets of a transportation agency's activities it is important to have a comprehensive framework. There are many frameworks for risk and resilience assessments for multiple sectors. After studying multiple R&R frameworks during the literature review phase, the research team developed an R&R framework building upon the most comprehensive and used frameworks including the AASHTO's framework from the Transportation Management Guide to incorporate risk management into Transportation Management Plans (TAMPs), the FHWA Vulnerability Assessment and Adaptation Framework[2], the risk management framework from the International Organization of Standardization ISO 31000[3] and the Risk Analysis and Management for Critical Asset Protection (RAMCAP Plus™)[4] framework among others. The enhanced framework is presented in Figure 3-1 and consists of four modules: (1) Organization, (2) Scoping, (3) Assessment, and (4) Management. An overview of each module is provided below.

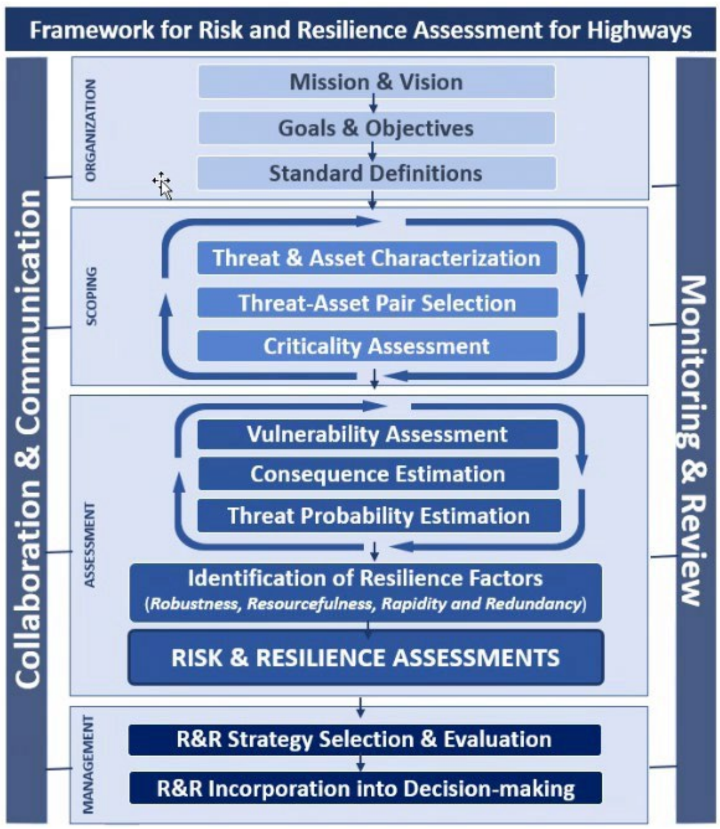

Figure 3-1. Risk and Resilience (R&R) Framework

[2] FHWA Vulnerability Assessment ad Adaptation Framework. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf
[3] ISO 31000 Risk Management Framework. https://www.iso.org/iso-31000-risk-management.html
[4] ASME RAMCAP Framework. https://www.researchgate.net/publication/230090388_Risk_Analysis_and_Management_for_Critical_Asset_Protection_RAMCAP_Plus

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Organization

Before a transportation agency can begin a risk and resilience analysis of its system, it must first answer key questions: 1) what is the organization's resilience vision, mission, and goals? and 2) what is the organization's risk tolerance. To design for resilience, engineers need to know what to design. Having clear definitions for risk and resilience will help agencies achieve their mission and goals. Defining a risk threshold or target is the first step. To define a risk threshold, it is helpful for an agency to consider its mission, values, goals, objectives, and definitions for risk and resilience.

- **Mission & Vision Statement.** A business mission statement is a simple action-oriented statement that explains the purpose of the business. The mission statement of the US DOT is "…to ensure our Nation has the safest, most efficient and modern transportation system in the world, which improves the quality of life for all American people and communities, from rural to urban, and increases the productivity and competitiveness of American workers and businesses." Mission statements for state DOTs typically follow a similar vein, explaining their purpose of providing mobility to the traveling public with added emphasis on safety, efficiency, sustainability, reliability, etc. A transportation agency's vision is its picture of how an improved transportation system in the future can enhance the economy and quality of life for the communities it serves. Vision statements are based on trend analysis of change in land use, demographics, population, economics, climate change, and so on. Goals and objectives are derived from the vision statement. It is key that risk and resilience are incorporated into the agency mission and vision as the initial step for successfully incorporating R&R efforts into the different agency areas.
- **Goals and Objectives.** The vision statement encompasses one or more goals, for example, safety and reliability. Objectives are the outcomes of pursuing a goal, and the success of an objective is assessed with performance measures. If safety is the goal, then fewer accidents are the objective, and the performance metric is the percentage reduction in accident rates. If reliability is the goal, one objective could be maintaining roadways in good working conditions. The performance measure is the percentage of lane miles maintained to a targeted condition. Similarly, resilience should be incorporated into the agency's goals and objectives, and risk and resilience metrics should be developed to measure if these goals and objectives are achieved.
- **Standard Definitions**. How DOTs define risk and resilience determines performance measures and investment priorities. For example, suppose the risk is defined as an adverse event's impact on a physical asset. In that case, the metric might be the percentage loss of asset replacement value, and the priority in investment is to harden the help. On the other hand, if resilience is defined in terms of the ability of an asset to rebound from an adverse event, the metric could be restoration time, and the investment priority is to build redundancy or enhance emergency response. (See the attached literature review in Appendix B for more discussion of risk and resiliency definitions).

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Scoping

Risk and resilience assessment begins with identifying a system's exposure to one or more threats. What is the spatial extent of the threat? Within that spatial extent what assets are exposed? In addition, how critical are the exposed assets to the network?

- **Threat and Asset Characterization**. Threat characterization includes developing a portfolio of hazard models or maps that accurately reflects the intensity and likelihood of threats within the agency's area of responsibility.
- **Threat-Asset Pair Selection.** Agencies develop the threat-asset matrix to show what assets are exposed to what threats and prioritize risk management decisions. With physical threats, deciding what are the important threats can be assisted with Geographical Information Systems (GIS) tools to intersect hazard maps with geospatial representations of physical assets. With non-physical threats, expert opinion and wargaming may be employed.
- **Criticality Assessment.** Criticality is the relative importance of an asset within the overall transportation system to the agency's larger goals and objectives which is providing equitable access to a reliable transportation system. Common variables used by state DOTs include Annual Average Daily Traffic (AADT), AASHTO road functional classification, whether on the National Highway System or evacuation route, distance from emergency services, location of under-represented population, equity, etc.

Assessment

Risk assessment is based on the fundamental risk equation, the product of asset vulnerability times consequences from disruptions times threat probability. This requires a study of the condition of the exposed assets and their ability to resist failure, what are the expected losses if an asset fails, and what is the likelihood that an event occurs. On the other hand, resilience assessment focuses more on the post-event cycle, and how fast a system can return to normal operations after an event. Resilience is a function of a system's robustness, resourcefulness, rapidity, and redundancy (The 4R's). (See the attached literature review in Appendix B for more discussion of risk and resiliency assessments).

- **Vulnerability Assessment**. Vulnerability is the probability that an asset is negatively impacted by a threat. The probability of damage or failure can be estimated based on multiple criteria such as asset condition state, age, design standard, existing countermeasures, and the severity of threat being considered. In addition, the analysis may consider multiple damage states (such as low, moderate, severe), and the probability of reaching each damage state is assigned a single value (between 0 and 1) or qualitatively described (e.g., low, medium, or high).
- **Consequence Estimation.** Consequences are the outcomes of an adverse event. Some of the possible consequences to be considered in the analysis include asset damage or

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replacement, user consequences caused by network disruption (delays), safety, operational, and environmental consequences, among others.

- **Threat Probability Estimation**. Determining the probability of a threat event can be qualitative, deterministic, or probabilistic. A deterministic analysis will employ either a simple frequentist approach whereby the likelihood of an event occurring is the number of events that have occurred over the entire period of record or a statistical approach whereby the historical record is fitted to a probability distribution. However, a probabilistic approach will involve more complicated, stochastic methodologies, such as Monte Carlo simulation.
- **Identification of Resilience Factors.** Threat likelihood, consequence, and vulnerability modeling account for the stresses that impact the system identifies the critical assets, and evaluate the vulnerability of exposed assets. Resilience factors provide context and assist decision-makers in how to best use the results of a risk and resilience assessment. AASHTO's definition of resilience, "The ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events," suggests different strategies that transportation planners can consider. Raw numbers generated from risk and resilience assessments may be of little value unless given a context of resilience metrics.
- **Risk and Resilience Assessments**. Risk is typically defined as the product of threat likelihood times vulnerability times consequences. On the other hand, resilience assessments may also consider the post-event consequences of disruptions to the network, such as the degradation in the level of service or loss of connectivity.

Management

Finally, risk and resilience management encompass the design and selection of mitigation and/or adaptation strategies. Alternative solutions take into consideration both the costs and benefits of each solution.

- **R&R Strategy Selection & Evaluation**. Risk management involves selecting strategies to reduce risk or enhance resilience based on a risk/resilience metric and economic analysis, such as the benefit-cost ratio, which will inform the decision-making process.
- **R&R Incorporation into Decision Making**. Transportation planners should use a two-step process to optimize their investment decisions: (1) define the objectives of proposed investments, and (2) define the measures of effectiveness. For example, for a proposed corridor improvement project that includes adding an HOV lane, the objective could be to reduce congestion and increase mobility. The measure of effectiveness could consist of a congestion index, economic development, and vehicle usage of the new HOV lane.

The risk and resilience framework for highways served as the basis for developing the overarching roadmap and supporting research problem statements. The R&R framework was discussed, enhanced, and validated during multiple stakeholder engagements.

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4. RESEARCH ROADMAP

Based on the information gathered during the literature review, the two industry engagements, and research team experience, we developed a research roadmap to develop and implement a highway framework/guidance to conduct a quantitative all-hazards risk and resilience (R&R) analysis.

The primary step in developing the roadmap is to define the current state of practice, the mission, and the goals and objectives to be accomplished with the research roadmap.

4.1. Roadmap Mission

The research team worked with the Project panel to create a mission statement for the research roadmap. The main mission of the research roadmap is to "create an efficient framework for state DOTs to implement consistent transportation asset risk and resilience processes within and among organizations for improved sustainability". The roadmap provides the necessary structure and steps to develop the framework/guidance as well as provides the steps for successful outreach and implementation. The outreach and implementation stages are as important as the steps for the development of the framework. Without proper outreach to stakeholders, as well as a comprehensive implementation plan, even the best framework will not be successful among practitioners.

4.2. Roadmap Goals

Similarly, the goal of the risk and resilience roadmap is to provide transportation agencies with a strategic plan consisting of objectives, desired outcomes, and tasks to be performed to advance the preparedness of the transportation sector for emerging threats and increase the resilience of the transportation system. The defined five goals are as follows:

1. Identify organizational development and outreach when implementing a risk and resiliency framework.
2. Define a consistent framework for risk and resilience assessment that identifies core processes and methods.
3. Identify tools to assist with risk and resilience assessments that align with the framework.
4. Identify technical skillsets and training to facilitate the conduct of risk and resiliency analyses.
5. Identify candidate research activities that advance key Roadmap elements.

4.3. Roadmap Thematic Lanes

Based on the literature review, gap assessment, and stakeholder engagements the research team identified knowledge gaps that were classified into three thematic lanes as follows:

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- **Thematic Lane A**. Organizational Development and Outreach
- **Thematic Lane B.** Risk and Resilience Assessment Processes
- **Thematic Lane C.** Technology and Tools

Thematic Lane A. Organizational Development and Outreach, and Implementation

As addressed in the final roadmap, Thematic Lane A addresses organizational capacity building, Institutional Organizational and Procedural (IOP) changes, and communication and collaboration. Capacity building includes actions designed to ensure an organization has a robust training program, guidance, and leadership support. IOP changes involve changing organizational culture from the traditional programmatic approach to incorporating risk-informed decision making. Communication and collaboration enhance organizational capacity by sharing data and mustering talent from across the organization.

The main focus of this thematic lane involves three main aspects related to the development, outreach, and implementation of the framework. The main factors included in this theme are:

- **Identification of key players** to oversee the creation of the framework/guidance and make sure the different steps proposed on the research roadmap are accomplished. The research team recommends the creation of an overseeing group or task force for this effort. The Task Force could be led by the sponsoring TRB Committee on Transportation Asset Management (AJE30) and formed by representatives of other TRB committees interested in this topic, such as the Committee on Critical Transportation Infrastructure Protection (AMR10), Committee on Systems, Enterprise, and Cyber Resilience (AMR40), and Committee on Extreme Weather and Climate Change Adaptation (AMR50) among others. The Taskforce will also be in charge of coordination among different groups working on the various topics proposed in the roadmap.
- **Development of outreach and communication strategies** to help agencies build and sustain relationships with inter and intra-agency partners to strengthen leadership and organizational buy-in for incorporating resilience into planning and other areas.
- **Development of a capacity-building plan** and material to provide the necessary training to leadership and staff to promote the institutionalization of risk and resilience education and practices at all levels of a transportation organization.
- **Identification of Internal Operation Procedures (IOP)** that are needed or need improvement and the development of **implementation strategies** for adoption of the guidance.
- **Pilot test** and implement framework/guidance with multiple state DOTs to make sure it meets the needs and capabilities of transportation agencies.

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Thematic Lane B. Risk and Resilience Assessment Processes

Whereas Thematic Lane A addresses how organizations can boost capacity to conduct R&R assessments, Thematic Lane B discusses the "how", especially how to conduct quantitative R&R assessments that are repeatable and verifiable. Recognizing that the terms "risk" and "resilience" have a complementary relationship, Lane B includes separate problem statements for risk assessment and resilience assessment. While risk management tends to focus on mitigating vulnerability (robustness) (Bruneau & Reinhorn, 2006), resilience strategies relate more to adaptability and post-event recovery—that is, all four of Bruneau's "4-R's", recovery, redundancy, rapidity, and robustness. Transportation organizations typically lack sufficient data to derive the necessary inputs for quantitative R&R models; i.e., threat likelihood, threat severity, vulnerability, and consequences. Thus, Lane B also considers tools and methodologies for harvesting historical data.

Finally, if organizations are to build more resilient systems, they must determine what they are building resilience to – in other words, what is the target? Here, the concept of risk appetite and risk tolerance comes into play. Lane B addresses these concerns with a problem statement that focuses on risk thresholds and metrics. The end product of Lane B will be a complete R&R manual that thoroughly explains the methodologies, data needs, and metrics that result from all supporting problem statements.

This thematic lane focuses on the development of quantitative methodologies to conduct risk and resilience assessments. The main factors included in this theme are:

- **Development of a process to identify critical highway infrastructure** that helps agencies to meet their mission and goals.
- **Development of standardized methodologies** to identify potential threats/hazards to the highway system, assess the vulnerability of highway assets from the identified threats, the expected consequences from asset damage and travel disruption, and conduct a complete quantitative risk and resilience analysis. This process will establish a collection of quantitative metrics for both risk and resilience.
- **Develop a comprehensive data collection plan and process** to compile threat, asset, and event data to support and validate their risk and resilience assessments.
- **Develop a methodology for selection of R&R thresholds** and selection of mitigation strategies to aid in project prioritization and help to incorporate R&R into decision making.

Thematic Lane C. Technology and Tools

Thematic Lane C facilitates the implementation of Lane A and Lane B, providing transportation organizations with a survey of publicly available tools as well as newly developed tools to fulfill the promises of both Lane A and Lane B, the capacity to conduct quantitative R&R assessments that are repeatable and verifiable.

These thematic lanes served as the basis for the development of the research roadmap to have a successful product with the necessary content and required implementation process. The three thematic lanes that integrate the research roadmap are explained in the sections below.

The focus of this thematic lane involves the identification, development, and promotion of the efficient application of risk and resilience analysis methodologies using the tools that facilitate the incorporation of risk and resilience analysis into decision making, resilience programs, and project design. These tools should be easy to use and integrate into existing technologies and tools currently used.

The private and public sectors offer many tools and methodologies for conducting risk and resilience analysis. This presents many challenges to transportation agencies—what is the appropriate tool, the required level of training or expertise, what data is needed, and the available data sources? Agencies complain that the tools currently available are too complex or require too much data too often.

4.4. Research Roadmap Phases and Duration

In addition to the selection and development of the three thematic lanes explained previously, the research team also selected the most appropriate duration for the research roadmap to successfully develop and adopt the R&R framework/guidance. The research roadmap is divided into three different phases:

- **Phase 1 -** Development of “Highway Risk & Resilience (R&R) Manual.”
- **Phase 2 -** Pilot testing and implementation of the “Highway Risk & Resilience (R&R) Manual.”
- **Phase 3 -** Development of tools and revision of “Highway Risk & Resilience (R&R) Manual.”

Phase 1 - Development of “Highway Risk & Resilience (R&R) Manual”

The first phase of the research roadmap has an approximate duration of 3 years. Phase 1 focuses on identifying the key players or task force that will oversee the development and implementation of the R&R Manual, the development of methodologies to conduct the quantitative R&R assessments for highway infrastructure, and the development of a data capture process and threshold methodology.

<u>Phase 1 Outcomes:</u>

- Taskforce to oversee the development of the R&R framework/manual, tools, and implementation.
- First version of the R&R framework/manual.

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Phase 2 - Pilot testing and implementation of "Highway Risk & Resilience (R&R) Manual"

Phase 2 of the research roadmap has an approximate duration of 2 years. In this phase, the focus is to pilot test the R&R Manual and methodologies developed in Phase 1 with multiple state DOTs. In addition, communication and collaboration practices will be developed, along with the capacity-building plan and training material based on the R&R Manual. Moreover, changes in Internal Operation Procedures (IOP) will be identified to develop strategies for successfully implementing the R&R Manual in different agency areas.

Phase 2 Outcomes:

- Pilot test of the first version of the R&R framework/manual and develop recommendations for improvement and revisions.
- Training material for transportation agencies on how to use the R&R framework/Manual.
- Communication and collaboration guidance to incorporate R&R into agency practices and decision-making.
- Guidance to identify IOP changes for R&R implementation.

Phase 3 - Development of tools and revision of "Highway Risk & Resilience (R&R) Manual"

Similar to Phase 2, this phase will also have a duration of 2 years. After pilot testing the R&R Manual in Phase 2, the focus of this phase will be to incorporate any changes identified during the pilots into the R&R Manual and to develop tools to conduct quantitative risk and resilience assessments. These tools should be developed in a way that is easy to use, used available data, and can be incorporated into existing processes and tools (e.g., TAM tools). In addition, the capacity-building plan and training material developed in Phase 2 should be expanded to incorporate the use of R&R assessment tools. The proposed research roadmap developed in this project is presented in Figure 4-1.

To accomplish the goals of each of the three phases of the research roadmap mentioned above, multiple research problem statements (RPSs) were developed. Detailed descriptions of each RPS are provided in Chapter 5.

As mentioned previously, each roadmap phase has multiple RPSs associated with it. The research team recommends bundling the projects in each phase as one large project or multiple dependent and coordinated projects. Bundling of projects will increase feasibility and coordination to avoid discrepancies in methodologies and delays in project development. The proposed bundling is presented in Figure 4-1 below.

Phase 3 Outcomes:

- Revised R&R framework/manual.
- R&R tools.
- Enhanced training material for R&R framework/manual and tools.

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Research Problem Statements and Bundling Recommendation

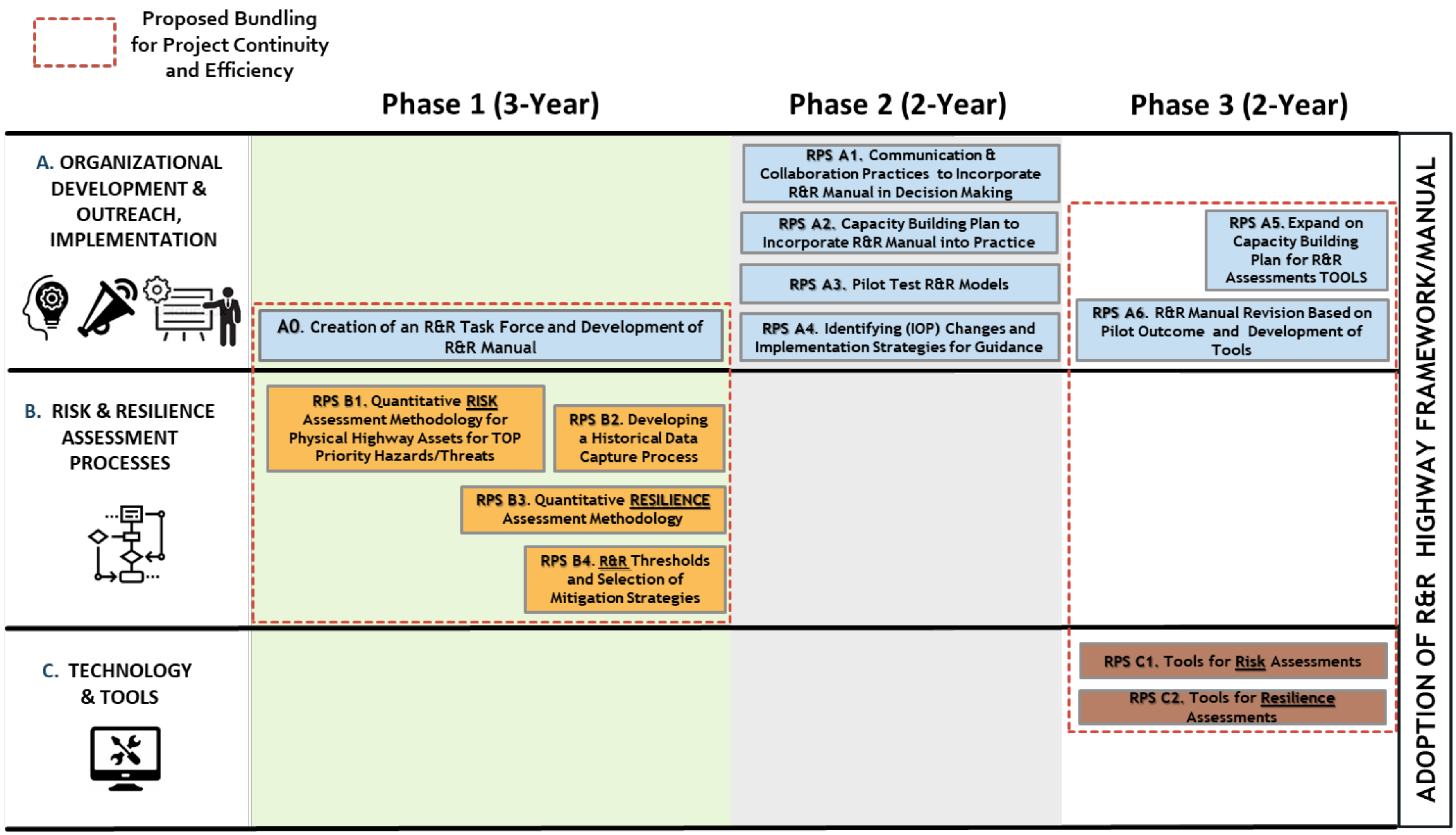

Figure 4-1 Research Roadmap

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5. RESEARCH PROBLEM STATEMENT DEVELOPMENT

The initial tasks on the project helped to identify the gaps and needs related to the development of the R&R Manual. Based on these gaps and the developed R&R framework, the research team developed 12 research problem statements (RPS). The RPS was developed by the three roadmap thematic lanes as presented in Figure 5-1.

Organizational Development, Outreach, & Implementation	Risk & Resilience Assessment Process	Technology & Tools	Knowledge Gaps	
●			**A1.** Creating Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management.	Lane A
●			**A2.** Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency (R&R) Assessments at Transportation Agencies.	
●			**A3**. Pilot Testing the Highway Risk and Resilience (R&R) Manual and Interface with Existing Asset Management Systems and Other Agency Functions	
●			**A4**. Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of the Highway R&R Manual.	
●			**A5.** Enhancing the Capacity Building and Implementation Plans to Incorporate Highway Risk and Resilience Manual and Tools	
●			**A6.** Revising the Highway Risk and Resilience Manual	
	●		**B1.** Establishing a Quantitative Multi-hazard **Risk** Assessment Methodology for Highway Assets	Lane B
	●		**B2.** Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments.	
	●		**B3.** Establishing a Quantitative **Resilience** Assessment Methodology for Transportation Highway Assets	
	●		**B4.** Establishing Considerations for Defining Risk and Resilience Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure	
		●	**C1.** Identifying and Developing Analytical Tools to Conduct **Risk** Assessments for Highway Assets.	Lane C
		●	**C2.** Identifying and Developing Analytical Tools to Conduct **Resilience** Assessments for Highway Assets.	

Figure 5-1. Highway R&R Manual Research Roadmap RPSs

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In addition, the proposed research problem statements (RPSs) grouped by the different roadmap phases are provided below:

Phase 1 - Development of "Highway Risk & Resilience Manual"

- RPS B1. Establishing a Quantitative Multi-hazard **Risk** Assessment Methodology for Highway Assets
- RPS B2. Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments.
- RPS B3. Establishing a Quantitative **Resilience** Assessment Methodology for Transportation Highway Assets
- RPS B4. Establishing Considerations for Defining Risk and Resilience (R&R) Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure

Phase 2 - Pilot testing and implementation of "Highway Risk & Resilience (R&R) Manual"

- **RPS A1.** Creating Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management.
- **RPS A2.** Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency Assessments (R&R) at Transportation Agencies.
- **RPS A3.** Pilot Testing Highway Risk and Resilience Assessment (R&R) Manual and Interface with Existing Asset Management Systems and Other Agency Functions
- **RPS A4.** Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of the Highway Risk and Resilience (R&R) Manual.

Phase 3 - Development of tools and revision of "Highway Risk & Resilience (R&R) Manual"

- **RPS A5.** Enhancing the Capacity Building and Implementation Plans to Incorporate Highway Risk and Resilience (R&R) Manual and Tools
- **RPS A6.** Revising Highway Risk and Resilience (R&R) Manual
- **RPS C1.** Identifying and Developing Analytical Tools to Conduct **Risk** Assessments for Highway Assets.
- **RPS C2.** Identifying and Developing Analytical Tools to Conduct **Resilience** Assessments for Highway Assets.

Full developed RPSs for each phase are presented in Appendix D of this report.

Currently, many NCHRP efforts are relevant to the topics proposed in the research roadmap and can be used as a starting point. The existing research must be streamlined for efficiency by taking advantage of successfully published resources to avoid duplication and improve continuity. Some of the current and past related projects are provided in Figure 5-2. One of the

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most important projects to highlight is NCHRP 23-24 *Methods to Allow Agencies to Incorporate Quantitative Risk Assessment at Project and Network Level.* This project may serve as the bases for generating the quantitative R&R framework and methodologies. However, the project is still in “pending” status for the selection of a contractor to perform the work at the time of development of this report.

Organizational Development & Outreach,	Risk & Resilience Assessment Process	Technology & Tools	Knowledge Gaps	Highway R&R Manual – Relevant NCHRP Projects
●	●	●	**NCHRP 23-24** Methods to Allow Agencies to Incorporate Quantitative Risk Assessment at Project and Network Level*	
	●		**NCHRP 02-26** Implementation of Life-Cycle Planning Analysis in a Transportation Asset Management Framework	
●	●	●	**NCHRP 08-36(121)** Successful Implementation of Enterprise Risk Management in State Transportation Agencies	
		●	**NCHRP 08-36(126)** Development of a Risk Register Spreadsheet Tool	
	●		**NCHRP 08-36(146)** Economic Resilience and Long-Term Highway/Transportation Infrastructure Investment	
●	●	●	**NCHRP 08-60** Guidebook on Risk Analysis Tools and Management Practices to Control Transportation Project Costs	
	●		**NCHRP 08-70** Uses of Risk Management and Data Management to Support Target-Setting for Performance-Based Resource Allocation by Transportation Agencies	
●			**NCHRP 08-93** Managing Risk Across the Enterprise: A Guidebook for State Departments of Transportation	
	●		**NCHRP 08-118** Risk Assessment Techniques for Transportation Asset Management	
●			**NCHRP 08-113** Integrating Effective Transportation Performance, Risk, and Asset Management Practices	
	●		**NCHRP 08-118** Risk Assessment Techniques for Transportation Asset Management	
	●		**NCHRP 08-124** Quantifying the Impacts of Corridor Management	
	●		**NCHRP 12-43** Bridge Life Cycle Cost Analysis	
	●		**NCHRP 15-61** Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure	
●	●		**NCHRP 15-80** Design Guide and Standards for Infrastructure Resilience	
	●		**NCHRP 20-07(378)** Assessing Risk for Bridge Management	
●			**NCHRP 20-24(74)** Executive Strategies for Risk Management by State Departments of Transportation	

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	●		**NCHRP 20-24(80)** Assessing the Economic Benefit of Transportation Infrastructure Investment in a Mature Surface Transportation System	
●	●	●	**NCHRP 20-59 (14C)** Understanding Transportation Resilience: A 2016-2018 Road Map	
●	●		**NCHRP 20-59(51)** A Security 101: A Physical & Cyber Security Primer for Transportation Agencies	
		●	**NCHRP 20-59(53)** FloodCast: A Framework for Enhanced Flood Event Decision Making for Transportation Resilience	
		●	**NCHRP 20-59(54)** Transportation System Resilience: Research Roadmap and White Papers	
		●	**NCHRP 20-59(55)** Transportation System Resilience: CEO Primer & Engagement	
	●		**NCHRP 20-83(5)** Climate Change and the Highway System: Impacts and Adaptation Approaches	
●	●		**NCHRP 20-101** Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change – Guidebook	
●	●	●	**NCHRP 20-117** Deploying Transportation Resilience Practices in State DOTs	
●	●	●	**NCHRP 20-125** Strategies for Incorporating Resilience into Transportation Networks	
●			**NCHRP 20-127** Business Case and Communications Strategies for State DOT Resilience Efforts	
●	●		**NCHRP 24-25** Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations	
●	●		**NCHRP 24-34** Reference Guide for Applying Risk and Reliability-Based Approaches for Bridge Scour Prediction	
●	●		**NCHRP 24-44** Guidelines for Managing Geotechnical Risks in Design-Build Projects	
	●		**NCHRP Synthesis 103** Risk Assessment Processes for Hazardous Materials Transportation	
	●		**NCHRP Synthesis 494** Life-Cycle Cost Analysis for Management of Highway Assets	
	●		**NCHRP Synthesis 20-05/Topic 50-15** Asset Management Approaches to Identifying and Evaluating Assets Damaged Due to Emergency Events	

*Project is still in "pending" status for selection of a contractor to perform the work at the time of development of this report

Figure 5-2. Highway R&R Manual – Relevant NCHRP Projects

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6. STAKEHOLDER ENGAGEMENT

The research team conducted a stakeholder engagement on September 22, 2021, to validate the research roadmap and research topics or problem statements developed for each thematic lane.

Twenty states plus the District of Columbia were represented (see Figure 6-1) with 35 participants from state DOTs, US DOT, FHWA, local agencies, academia, and the private sector. Before the workshop, all invitees were sent a read-ahead packet which included detailed descriptions of the following:

1. Framework for conducting quantitative risk and resilience assessments to physical highway infrastructure.
2. Research roadmap to develop and adopt a highway framework/guidance for R&R assessments, including graphic illustrations of two research roadmap options.
3. Complete catalog of 12 proposed research problem statements (RPSs).

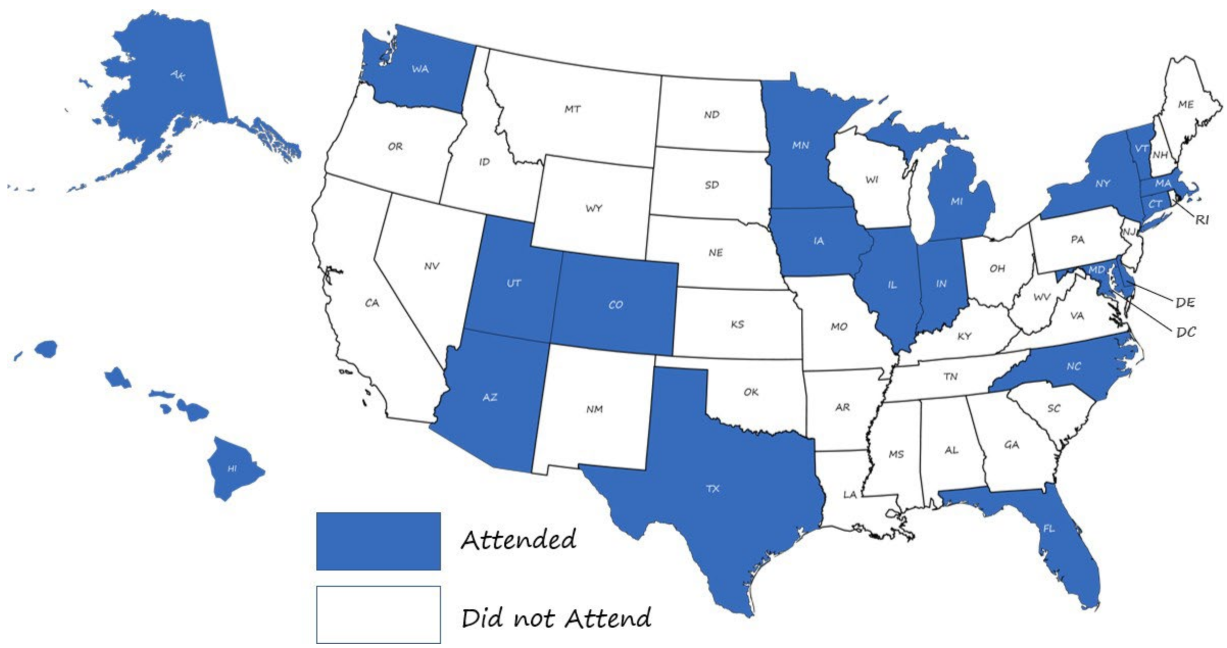

Figure 6-1. Map of Geographical Distribution of Workshop Participants

The research team presented two different roadmap options with different durations and approaches for research development: (1) Option 1, a comprehensive single project to be executed over a 3-year time frame, and (2) Option 2, a multi-project track to be executed over a 3-year time frame plus a two-year follow-up for pilot studies and tool development. The workshop participants overwhelmingly selected option 2, the multi-project roadmap.

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In addition to the roadmap options, a total of 12 research problem statements were provided for feedback. The goal of the research team was to engage stakeholders in a discussion, supplemented with an interactive online platform, to obtain feedback concerning the selection and prioritization of RPS as well as stakeholder preference for the two proposed research options.

The industry workshop for roadmap validation was conducted in two parts – a PowerPoint presentation, followed by an interactive session with Mural, a virtual whiteboard that facilitates visual collaboration. The high-level takeaways from the stakeholder engagement included:

- The participants agreed that the roadmap should be divided into multiple projects rather than a single, comprehensive project.
- The participants stressed a preference for a 3-year roadmap to produce the most important deliverables as soon as possible, with a 2-year follow-on to produce needed but less critical features.
- Risk and resilience should not be completely siloed but treated as interrelated.
- The framework should be consistent and focus on highway assets.
- Tools and methodologies should be simple as possible and not too expensive. Do not try to make models perfect.
- Leadership buy-in is crucial, but this requires being able to demonstrate the benefits and costs of doing risk and resilience assessments.
- There are different levels of assessment: planning vs. project scoping.

Feedback from the industry workshop helped to tailor and enhance the proposed RPSs. Following the industry workshop, the research team had multiple conversations with the project panel members regarding the best approach in terms of duration, phases and research topics, and problem statements. In addition, the research team coordinated with the TRB Committee on Transportation Asset Management (AJE30) and aligned the research roadmap to meet the technical panel and AJE30 committee expectations in terms of the development of a program to support the research associated with the development and implementation of the risk and resilience manual and tools.

The research team and technical panel determined that the option-2 roadmap, a 3-year time period, plus a 2-year follow-up, was too ambitious. An additional two years would be required for both revisions of the final R&R guidebook and tool development. The research team briefed the panel on its recommendations on November 22nd, 2021, and received approval to continue with the revised roadmap, consisting of three phases (presented in Chapter 3, Figure 4-1): phase 1 focuses on developing assessment methodologies, phase 2 focuses on testing the methodologies and agency capacity building, and phase 3 focuses on tool development and revision of the R&R manual.

The complete technical memorandum documenting the workshop can be found in Appendix E of this report.

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7. RESEARCH OUTPUTS, RECOMMENDATIONS, AND NEXT STEPS

This section summarizes the outputs of this NCHRP 08-129 project, recommendations for future research, and recommended next steps.

7.1. Research Outputs

In addition to this final research report, other outputs of this research include:

- **Implementation and Communication Technical Memorandum** – The implementation plan recommends actions for disseminating and promoting the research products of NCHRP 23-09. The plan describes channels, venues, and professional organizations that will potentially assist in sharing and marketing the research products. See Appendix F for a stand-alone implementation plan for this project.

- **Communication Material** –The communication material is designed to support the Implementation and Communication Plan and includes a *fact sheet or flyer* and *a set of presentation slides*. The fact sheet concisely helps to communicate the importance of the development and implementation of a risk and resilience manual. The set of presentation slides provides an overview of the project and can be used to advertise the outcomes of NCHRP 23-09. See Appendix G for the communication products developed for this project.

7.2. Findings and Recommendations

For additional research to be useful for transportation agencies, it should speak to actionable findings and recommendations. Analytical risk assessment methods to support risk-based asset management processes are the best approach to support an all-hazards risk and resilience analysis for the highway system. The research made actionable recommendations through four major roadmap themes for which all the RPS were created to help address**:**

- **Organizational Development and Outreach** | Development of organizational work to start creating the framework/guidance as well as all the outreach and communication strategies and tasks for producing the framework/guidance. In addition, it also will include the implementation strategies for the successful adoption of the framework/guidance.

- **Risk and Resilience Assessment Processes** | Development of processes to identify the most critical highway infrastructure, threats to their system, assess the vulnerability of their system and conduct a complete risk and resilience analysis. In addition, transportation agencies need a comprehensive data collection plan to compile threat, asset, and event data to support and validate their risk and resilience assessments.

- **Technology and Tools** | Identify or establish the appropriate tools, required level of training or expertise, data needed, and available data sources required to implement the framework/guidance.

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- **Technical Capacity Building** | Build and maintain a robust risk and resilience program, transportation agencies need adequate funding, training, guidance, and support from leadership.

7.3. Opportunities for Implementing

The research will likely be most helpful to agencies that need to adopt a risk and resilience highway framework/guidance to conduct an all-hazards risk and resilience (R&R) assessment. These opportunities may include:

- Development of research problem statements that will address the types of activities needed to support the development and adoption of an all-hazards risk and resilience analysis. These have been included in the final report and should be considered for funding moving forward. This also includes the prioritization and customization of specific needs within the transportation community, due to agency maturity or other specific needs.

- Development of an outreach plan that describes channels, venues, and professional organizations that will potentially assist in sharing and marketing the research products which include the summaries of the industry workshop, guidance, and research problem statements. The following should be considered:

    - **AASHTO committees:** The AASHTO structure is such that it affects and supports all state DOTs. The committees within AASHTO can effectively garner support to move these research problem statements forward. We specifically recommend enhancing collaboration with the following AASHTO committees and subcommittees: Committee on Performance-Based Management (CPBM), Subcommittee on Risk Management, and Committee on Transportation System Security and Resilience (CTSSR). There are other committees and councils within AASHTO that could benefit from this research such as the Committee on Planning as well as the Highways and Streets Council.

    - **TRB committees:** TRB is comprised of many standing committees within its Technical Activities Division that are interested in and support research on the topic of resiliency. TRB is comprised of academia, consultants, government officials, and other transportation professionals. These committees can help to share the findings of this research. We specifically recommend the following TRB standing committees:
        - AJE30 – Asset Management
        - AJE20 – Performance Management
        - AJE10 – Strategic Management
        - ATO40 – Risk Management
        - AMR10 – Critical Infrastructure Protection
        - AMR50 – Extreme Weather and Climate Change Adaptation

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    - AEP10 – Transportation Planning Policy and Process
    - AT040 – Subcommittee on Risk Management

  - **State DOTs:** Each state DOT has interested staff and teams focused on resiliency. The products and results from this research should be forwarded to each state DOT for further consideration.

- Development of a communications plan that describes goals, objectives, target audience, channels, tools, and key themes to educate the value of research products.
  - Within the communication plans, various types of communication methods such as newsletters, podcasts, and other media are criterial to sharing the information that was gathered during this research.

- Development and dissemination of the final research roadmap to advance the preparedness of the transportation sector for emerging threats and increase the resilience of the transportation system.

Research that builds on NCHRP 23-09 speaks to both the actionable findings of this project and an agency's most effective implementation opportunities. The RPSs identified in this research project should be contemplated moving forward and are organized into four categories:

- **Time-Sensitive** | These concepts may be useful for the 2022 NCHRP round and as such may need to be submitted in 2022 or 2023.
- **Sequence Needed for Success** | These concepts build directly from the findings of this research and have similar approaches and lines of inquiry.
- **High-Value Assistance** | These concepts were suggested or inspired by participants in 23-09 workshops as well as the project panel and could bring significant benefits to agencies in the areas discussed in this work.
- **Ongoing Efforts** | These concepts build upon prior or current research efforts that relate to the areas discussed in this work.

7.4. Next Steps

The research team recommends the next steps:

- *Formal adoption and approval of the Glossary of Terms and the RPSs contained within this research*
- *Identify champions (within the AASHTO committee structure) and map out the sequence for necessary funding through NCHRP and/or other funding sources*
- *Create a team or Taskforce that initiates the implementation and communication plan and continues to elevate it until all RPSs are underway.*

Research approval or adoption/integration of the proposed research roadmap and RPS in this document would be an excellent next step for NCHRP and other researchers to take in helping

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to develop and implement the R&R Highway Manual realizing the value and industry need for this research.

8. CONCLUSION

This research validated the need for the development of a framework and tools to help transportation agencies conduct quantitative risk and resilience assessments for their transportation infrastructure and meet the requirements of multiple federal regulations. In addition, it identified the gaps and successes in the state of practice to help with the development of products that will be easily incorporated into current practices.

While this research roadmap addresses highway assets explicitly, the research team recognizes that the R&R framework described in the roadmap can be expanded to address a multi-modal system. Such a framework would have to take on a system-of-systems approach, addressing the complexity of many interdependent systems, as well as the impact of interactive and multiplicate threats, both natural and anthropogenic. Graph theory, topological measures, and travel demand modeling, as described by D'Ayala [3], and Markolf's "Pathways of Disruption" [4], offer some strategies toward a more system-wide approach for R&R assessment.

The work completed in NCHRP 23-09 provides the necessary steps (framework, roadmap, and research problem statements) to guide the research community to develop a risk and resilience manual and tools to conduct quantitative risk and resilience assessments.

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APPENDIX A – GLOSSARY OF TERMS

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NCHRP PROJECT 23-09

SCOPING STUDY TO DEVELOP THE BASIS FOR A HIGHWAY STANDARD TO CONDUCT AN ALL-HAZARDS RISK AND RESILIENCE ANALYSIS

TASK 1.A DELIVERABLE – GLOSSARY OF TERMS

Prepared by
AEM Corporation
Jacobs Engineering Group
Cambridge Systematics

February 17, 2021

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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Executive Summary

The primary objectives of the NCHRP 23-09 Project, Scoping Study to Develop the Basis for a Highway Framework to Conduct an All-Hazards Risk and Resilience Analysis, are to (1) develop a comprehensive and consistent set of risk and resilience related terminology and (2) formulate a research roadmap to establish a framework that supports quantitative assessments of all-hazard risk and resilience for State and local departments of transportation. The NCHRP 23-09 Research Project in its execution, will facilitate the communication of ideas garnered through literature review, surveys, and subject matter expert feedback. The first step in this research is to develop a glossary of terms in this document.

This glossary intends to merge the language surrounding all-hazards risk and resilience and bring together the multiple authoritative definitions for review as an industry. The intent is to evolve this glossary to reduce confusion and increase clarity toward a comprehensive and consistent set of risk-and-resilience-related terminology for transportation agency use. The current glossary contains 188 words with definitions drawn from 91 sources.

Definitions were derived to the extent possible from sources published by the transportation sector, such as the Federal Highway Administration (FHWA) Planning Glossary, the TRB Glossary, various NCHRP reports, and the American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management (TAM) Guide. Some definitions are based on the Federal Emergency Management Administration (FEMA) language. Additionally, specific definitions are derived from glossaries contained in the American Society of Mechanical Engineers (ASME) Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus manual and the American Water Works Association (AWWA) J100 standard. Multiple definitions are included in this glossary to provide context and to help transportation professionals understand the nuance and contextual differences among authoritative sources.

The remainder of this document includes a single table listing all 188 terms, followed by each term with accompanying definition and source attribution in alphabetical order.

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Glossary Terms List and Page Number

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Absorptive Capacity

- "The ability of the transportation system to absorb shocks and stresses and maintain normal functioning." (Weilant, Strong, & Miller, 2019)

Acceptable Risk

- "The level of potential losses that a society or community considers acceptable given existing social, economic, political, cultural, technical, and environmental conditions. UNISDR Editor's Note: In engineering terms, acceptable risk is also used to assess and define the structural and non-structural measures that are needed in order to reduce possible harm to people, property, services, and systems to a chosen tolerated level, according to codes or "accepted practice" which are based on known probabilities of hazards and other factors." (United Nations Office for Disaster Risk Reduction (UNISDR) Terminology, 2016)
- "That level of risk that is sufficiently low that society is comfortable with it. Society does not generally consider expenditure in further reducing such risks justifiable." (Australian National Committee on Large Dams, 1994)
- "Degree of human and material loss that is perceived by the community or relevant authorities as tolerable in actions to minimize disaster risk." (United Nations, Department of Humanitarian Affairs, 1992)

Adaptation

- "Adjustment in natural or human systems in anticipation of or response to a changing environment that effectively uses beneficial opportunities or reduces negative effects." (FHWA, 2014)
- "The process of adjusting to new (climate) conditions in order to reduce risks to valued assets." (FHWA, 2020)
- "Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects." (Weilant, Strong, & Miller, 2019)

Adaptive Capacity

- "The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences." (U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 2008)
- "The ability of a person, asset, or system to adjust to a hazard, take advantage of new opportunities, or cope with change." (United States Global Change Research Program, 2020)
- "The ability of a transportation asset or system to adjust, repair, or flexibly respond to damage caused by climate variability or extreme weather." (FHWA, 2020)

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- “The ability of the system to change in response to shocks and stresses to maintain normal functioning.” (Weilant, Strong, & Miller, 2019)

Adversary

- “Any individual, group, organization, or government that conducts activities, or has the intention and capability to conduct activities, detrimental to critical infrastructure or key assets. Adversaries may include intelligence services of host nations or third-party nations, political and terrorist groups, criminals, rogue employees, and private interests. Adversaries can include site insiders, site outsiders, or the two acting in collusion.” (AWWA, 2014)

All-Hazards

- “An approach for prevention, protection, preparedness, response, and recovery that addresses a full range of threats and hazards, including domestic terrorist attacks, natural and manmade disasters, accidental disruptions, and other emergencies.” (DHS, 2006)

All-Hazards Approach

“An integrated hazard management strategy that incorporates planning for and consideration of all potential natural and technological hazards.” (National Science and Technology Council (NTSC), Committee on the Environmental and Natural Resources, Subcommittee on Natural Disaster Reduction, 1996)

All-Hazards Preparedness

- “The term ‘all-hazards preparedness’ refers to preparedness for domestic attacks, major disasters, and other emergencies.” (HSPD-8 (Homeland Security Presidential Directive), 2003)

Analysis

- “Inspection and analysis to check whether a standard or set of guidelines is being followed, that records are accurate, or that efficiency and effectiveness targets are being met” (ASME, 2009).
- “The separation of an intellectual or material whole into its constituent parts for individual study. In the context of risk management, a broad, unconstrained consideration of risk and its component factors aimed at improving one’s ability to make better decisions.” (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Annual Exceedance Probability (AEP)

- “The estimated probability that an event of specified magnitude will be exceeded in any year.” (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Assessment

- “The application of a method or procedure to measure or produce a decision- support product, with specific constraints in scope.” (ASME, 2009)

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Asset

- "An item of value or importance. Assets may include physical elements (tangible property), cyber elements (information and communication systems), and human or living elements (critical knowledge and functions of people)." (ASME, 2009)
- "(transportation system): Essentially any feature built and maintained on a highway (e.g., pavement, bridge, culvert, sign, and embankment)." (Flannery, Pena, & Manns, 2018)
- "An item of value or importance. In the context of critical water and wastewater infrastructure, an asset is something of importance or value that if targeted, exploited, destroyed, or incapacitated could result in injury, death, economic damage to the owner of the asset or to the community it serves, destruction of property, or could profoundly damage a nation's prestige and confidence. Assets may include physical elements (tangible property), cyber elements (information and communication systems), and human or living elements (critical knowledge and functions of people)." (AWWA, 2014)

Asset Class

- "Assets with the same characteristics and function (e.g., bridges, culverts, tunnels, pavements, or guardrail) that are a subset of a group or collection of assets that serve." (FHWA, n.d.)

Asset Condition

- "The actual physical condition of an asset." (FHWA, n.d.)
- "Refers to an asset's current state, as specifically defined by its appearance, perceived level of service, and observed physical state, whether or not it impacts its performance" (AASHTO, 2013)
- "condition relates to the structural integrity of an asset. Condition can be measured visually or with instruments and over time condition will almost always deteriorate without agency intervention." (AASHTO, 2013)

Asset Management

- "The practice of taking a comprehensive view of the entire portfolio of resources available in order to achieve system-wide agency goals at optimal cost-benefit. This includes the ability to show how, when, and why resources were committed." (Nakanishi & Auza, 2015)
- "Asset management is the process responsible for tracking and reporting the value and ownership of financial assets throughout their lifecycle. Asset management is part of an overall service asset and configuration management process." (DRI International, Inc., 2021)
- "A strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain the desired state of good repair over the life cycle of the assets at minimum practicable cost." (FHWA, n.d.)

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- (Transportation) “Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives.” (Systematics, 2009)

Asset Management Plan

- “Means a document that describes how a State DOT will carry out asset management as defined in this section. This includes how the State DOT will make risk-based decisions from a long-term assessment of the National Highway System (NHS), and other public roads included in the plan at the option of the State DOT, as it relates to managing its physical assets and laying out a set of investment strategies to address the condition and system performance gaps. This document describes how the highway network system will be managed to achieve State DOT targets for asset condition and system performance effectiveness while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets. The term asset management plan under this part is the risk-based asset management plan that is required under 23 U.S.C. 119(e) and is intended to carry out asset management as defined in 23 U.S.C. 101(a)(2).” (FHWA, n.d.)

Asset Replacement Cost

- “The anticipated cost to replace a damaged highway asset utilizing planning level estimates of unit costs.” (CDOT, 2020)

Benefits

- “The difference between the risk and resilience levels without the option and those with the option in place (also called “gross benefits”).” (AWWA, 2014)

Benefit/Cost Analysis/Ratio

- “A benefit-cost ratio (BCR) is a ratio used in a cost-benefit analysis to summarize the overall relationship between the relative costs and benefits of a proposed project. BCR can be expressed in monetary or qualitative terms. If a project has a BCR greater than 1.0, the project is expected to deliver a positive net present value to a firm and its investors.” (Hayes, 2020)
- “Benefit-Cost Analysis, also referred to as Cost-Benefit Analysis, is a systematic process for calculating and comparing the benefits and costs of a project for two purposes:
    - to determine if it is a sound investment (justification/feasibility)
    - to see how it compares with alternate projects (ranking/priority assignment)” (Transportation Research Board, n.d.)

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Best Practice

- "Proven activities or processes that have been successfully used by multiple organizations." (DRI International, Inc., 2021)

Bridge Management System (BMS)

- "A systematic process that provides, analyzes, and summarizes bridge information for use in selecting and implementing cost-effective bridge construction, rehabilitation, and maintenance programs." (FHWA, 2017)

Buffer Zone

- "The outside area around an asset created by the combination of physical distance, barriers, security measures and other protective features that contributes to its protection from physical attack." (ASME, 2009)

Business Continuity

- "The ability of an organization to continue to function before, during, and after a disaster." (DHS, 2006)
- "…the term business continuity encompasses the gamut of mechanisms that maintain continuity in business, including all forms of problem resolution and preventive mechanisms like quality assurance and security." (Wainschel, 2006)

Business Risk

- "Risk that internal and external factors, such as inability to provide a service or product, or a fall in demand for an organization's products or services will result in an unexpected loss." (DRI International, Inc., 2021)

Capability

- "The ability to cause an unwanted event or undertake an attack. In security analysis, the capability is one factor of a threatening adversary." (ASME, 2009)

Capability Maturity Framework (CMF)

- "The CMF is based on self-evaluation regarding the key process and institutional capabilities required from a transportation agency (or group of agencies) to achieve effective TSMO. This framework is adapted from a concept developed in the information technology industry called the Capability Maturity Model (CMM), which has been tailored to the transportation community. The CMF identifies the six key dimensions of process and institutional capability that directly relate to improving program effectiveness: business processes; systems and technology; performance measurement; culture; organization and workforce; collaboration." (FHWA, 2002)

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Change Averse

- "A strong opposition to changing practices or beliefs." (Asam, Bhat, Dix, Bauer, & Gopalakrishna, 2015)

Climate Change

- "Refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events." (FHWA, 2014)

Climate Stressor

- "A condition, event, or trend related to climate variability and change that can exacerbate hazards." (United States Global Change Research Program, 2020)
- "Acute and long-term weather events and trends that have an effect on an asset or service. Among others, stressors include extreme temperature events and precipitation events, drought, sea level rise, storm surge, intense storms (e.g., hurricanes and tropical storms), strong winds, blizzards, humidity, permafrost thaw, and long-term temperature and precipitation trends." (U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 2008)

Comprehensive Emergency Management

- "An integrated approach to the management of emergency programs and activities for all four emergency phases (mitigation, preparedness, response, and recovery), for all types of emergencies and disasters, and all levels of government and the private sector. "(Blanchard, 2006)

Conditional Probability

- "The probability of an outcome, given the occurrence of some event. For example, given that a flood has reached the crest of an embankment dam, the probability of the dam failing is a conditional probability." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)
- "Probability of an event based on the assumption/condition that a previous event has occurred. For example, in an event tree branch, at any node, the sum of the conditional probabilities associated with each of the events/branches immediately following that node should equal 1." (ASME, 2009)

Conditional Risk

- "A measure of risk that focuses on consequences, vulnerability, and adversary capabilities but excludes threat frequency. It is used as a basis for making long-term risk management decisions. The adversary capabilities, countermeasures and residual vulnerability are often combined into a measure of the likelihood of adversary success." (ASME, 2009)

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Consequence

- "The outcome of an event occurrence, including immediate, short, and long-term, direct, and indirect losses and effects. Loss may include human fatalities and injuries, monetary and economic damages, and environmental impact, which can generally be estimated in quantitative terms. In addition, consequences may also include less tangible and therefore, less quantifiable effects, including governance impacts, political ramifications, morale, and psychological effects, reductions in operational effectiveness or military readiness, or other impacts." (ASME, 2009)
- "The immediate, short- and long-term effects of a malevolent attack or natural hazard. These effects include losses suffered by the owner of the asset and by the community served by that asset. They include human and property losses, environmental damages, and lifeline interruptions. Property damage and losses from interruption of operations are expressed in monetary units. Consequences involving loss of life, injury, loss of lifelines, and environmental damage may be measured in any combination of two of the following: (1) natural units reported and considered individually (e.g., fatalities, number of serious injuries, losses in dollars); (2) converted to a single, summary economic value, reported, and considered as a single loss indicator; and (3) in predefined ranges represented by the RAMCAP "bins" (AWWA, 2014).
- A subsequent result (usually negative) that follows from damage to or loss of an asset. Quantifying potential consequences is an important part of determining risk (United States Global Change Research Program, 2020).
- "The result of a terrorist attack or other hazard that reflects the level, duration, and nature of the loss resulting from the incident. For the purposes of the NIPP, consequences are divided into four main categories: public health and safety, economic, psychological, and governance." (DHS, 2006)

Consequence-Mitigation

- "A series of planned and coordinated actions or system features designed to reduce or minimize the damage caused by attacks (consequences of an attack); support and complement emergency forces (first responders); facilitate field-investigation and crisis management; and facilitate rapid recovery and reconstitution. May also include steps taken to reduce short- and long-term consequences, such as providing alternative sources of supply for critical goods and services. Mitigation actions and strategies are intended to reduce the consequences of an incident, whereas countermeasures are intended to reduce the probability that an attack will occur or will cause a failure or significant damage if it occurs." (AWWA, 2014)
- "The planned and coordinated actions or system features designed to reduce or minimize the damage caused by attacks or natural hazard events (consequences of an attack or event); support and complement emergency forces (first responders); facilitate field- investigation ,and crisis management response; and facilitate rapid recovery, reconstitution, and resumption of function (resilience). Consequence-mitigation may also include steps taken to enhance resilience by reducing short- and long-term impacts, such as providing alternative sources of supply for critical goods and services. Consequence-mitigation actions and strategies are intended to reduce the consequences/impacts of an event, whereas countermeasures are intended to reduce the

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probability of the event occurring, and/or the probability that an attack will succeed in causing a failure or significant damage." (ASME, 2009)

Consequence-Mitigation Features

- "Those attributes, e.g., planned responses of system operators or automatic responses of engineered safety systems, of the asset or system that limit the impacts of a threat that has occurred." (ASME, 2009)

Consequence-Mitigation Strategies

- "The set of both internal consequence-mitigation features and other responses, e.g., by agencies outside the boundaries of the asset, such as emergency response or first responders, that limit the impacts of a threat that has occurred." (ASME, 2009)

Consequence Analysis

- "Is the identification and estimation of the worst reasonable consequences generated by each specific asset/threat combination." (ASME, 2009)

Continuity of Operations (COOP)

- "The ability to recover and provide services sufficient to meet the minimal needs of users of the system/agency. This ability to continue essential agency functions across a wide spectrum of emergencies will not necessarily limit COG functions." (2004)

Costs

- "When used to evaluate an option, the present value of all forward negative cash flows, including both investment and operating outlays (also known as "life-cycle costs"). Costs follow the principle of forward costing only, i.e., no previous outlays ("sunk" costs) are to be included. The only exception to this is where the user is a taxable organization, when unused depreciation can affect forward tax liabilities." (ASME, 2009; AWWA, 2014)

Countermeasures

- "An action taken, or a physical capability provided for the principal purpose of reducing or eliminating vulnerabilities or reducing the likelihood of occurrence of attacks. Countermeasures are often elements in a comprehensive and holistic security system designed to defend, detect, delay, deter or devalue an attack, i.e.,
    - Defend against attack by delaying or preventing an aggressor's movement toward the asset or use of weapons and explosives.
    - Detect an aggressor who is planning or committing an attack or the presence of a hazardous device or weapon.
    - Delay or slow the actions of an adversary to the point that a successful attack takes longer than expected or desired, during which time, defenses may intervene." (ASME, 2009)

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- "What is in place or could be put in place to reduce the vulnerability of an asset, and/or the probability that an attack will succeed in causing failure or significant damage." (Flannery, Pena, & Manns, 2018)
- "All measures taken to counter and reduce a hazard or consequences of a hazard. They most commonly refer to engineering (structural) measures but can also include other non-structural measures and tools designed and employed to avoid or limit the adverse impact of natural hazards and related environmental and technological disasters." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)
- "For the private sector, crisis management is that transition from normal business decision-making processes to a highly streamlined process aimed at containing the initiating event, maintaining essential operations, and recovery of normal business conditions as quickly as possible." (AWWA, 2014)

Crisis Management

- "For the private sector, crisis management is that transition from normal business decision-making to a highly streamlined activity aimed at containing the initiating event, maintaining essential operations and recovery of normal business conditions as quickly as possible." (AWWA, 2014)

Critical Assets

- "An asset considered to be essential to the function of a facility or infrastructure component. In the context of national critical infrastructure and key resource (CI/KR) protection**,** a CI/KR asset is something of importance or value which, if targeted, exploited, destroyed, or incapacitated could result in large scale injury, death, economic damage, destruction, or property, or could profoundly damage a nation's prestige and confidence." (ASME, 2009)
- "An asset whose absence or unavailability would significantly degrade the ability of an organization to carry out its mission. The criticality of an asset can vary depending on the decisions to be made and perspective of the analyst." (ASME, 2009)
- "Assets, that if lost or damaged, would severely degrade or curtail an owner's ability to perform core functions or its mission." (Flannery, Pena, & Manns, 2018)
- "An asset of such strategic importance to the performance of essential functions that its incapacitation or destruction would have a very serious or debilitating effect on an organization's ability to perform the function(s)." (CDOT, 2020)
- "An asset whose absence or unavailability would significantly degrade the ability of an organization to carry out its mission. The criticality of an asset can vary depending on the decisions to be made and perspective of the analyst." (ASME, 2009)

Critical Infrastructure

- "Systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national

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economic security, national public health or safety, or any combination of those matters." (Critical Infrastructure Protection Act of 2001, Public Law 107-56, Sec. 1016(6))

- "The assets, systems, facilities, networks, and other elements that society relies upon to maintain national security, economic vitality, and public health and safety." (DHS, 2019)
- "Physical assets whose incapacity or destruction would have a debilitating impact on the economic or physical security of an organization, community, nation, etc." (DRI International, Inc., 2021)
- "The incapacity or failure of which would have a debilitating impact on national or regional economic security, national or regional energy security, national or regional public health or safety, or any combination of those matters." (Public Law 114-94, Fixing America's Surface Transportation Act, 2015)
- "Assets, systems, and networks, whether physical or virtual, so vital to the United States that the incapacity or destruction of such assets, systems, or networks would have a debilitating impact on security, national economic security, public health or safety, or any combination of those matters." (DHS, 2006)

Criticality

- "A measure of the importance of an asset to the resilience of an overall system." (CDOT, 2020)
- "Asset criticality is a key concept, relating to the importance of the asset and the level of risk that it may be exposed to. Criticality can be a driver of data collection efforts." (AASHTO, 2013)

Damage Assessment

- "An appraisal or determination of the effects of the incident on humans, on physical, operational, economic characteristics, and the environment." (DRI International, Inc., 2021)
- "Assets, systems, and networks, whether physical or virtual, so vital to the United States that the incapacity or destruction of such assets, systems, or networks would have a debilitating impact on security, national economic security, public health or safety, or any combination of those matters." (DHS, 2006)

Decision Criteria

- "The set of information and assumptions on which a decision is based. These generally include both technical and "political" factors, and typically involve significant uncertainty." (ASME, 2009)

Decision Tree

- "A diagram used to select the best course of action in uncertain situations." (California Department of Transportation, 2003)

Delay

- "Use of security countermeasures to slow the actions of an adversary to the point that a successful attack takes long enough to be interdicted or longer than expected or desired by the adversary." (AWWA, 2014)

Dependency

- "The reliance of an asset, system, network, or collection thereof, within or across sectors, on input, interaction, or another requirement from other sources in order to perform mission objectives." (AWWA, 2014)

Dependency Hazard/Threat

- "A dependency the denial of which has the potential to disrupt the function of the asset, system, etc." (AWWA, 2014)

Design Standard

- "Design standards are defined as standards which have been agreed upon by various regulating bodies and refer to all aspects of defining quality and methods of fabrication or installation of materials and equipment." (AutoQuiz: What is the Definition of a Design Standard? 2021)

Deterministic Analysis/Models

- "Describing a process with an outcome that is always the same for a given random, which describes a process with an outcome that can vary even though the inputs are the same. Deterministic analysis contrasts with probabilistic analysis." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Disaster

- "An occurrence that has resulted in property damage, deaths, and /or injuries to a community." (FEMA, 1990)
- "A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources." (National Science and Technology Council (NTSC), Committee on the Environmental and Natural Resources, Subcommittee on Natural Disaster Reduction, 1996)
- "A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community/society to cope using its own resources." (UNISDR, 2002)

Domestic Incident Management

- "For the Federal Government, domestic incident management is predominantly a DHS function to coordinate federal operations within the United States to prevent, prepare for, respond to, and

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recover from terrorist attacks, major disasters, and other emergencies. It includes measures to identify, acquire and plan the use of resources needed to anticipate, prevent and/or resolve a threat or act of terrorism. State and local authorities participating in this response may view it as crisis management, which includes traditional law enforcement functions, such as intelligence, surveillance, tactical operations, negotiations, forensics, and investigations." (ASME, 2009)

Economic Impacts/Loss

- "For risk management at two levels: (1) the financial consequences to the organization; and (2) the economic consequences to the regional metropolitan community the organization serves." (ASME, 2009)

Ecosystem Services

- "Benefits that humans receive from natural systems." (United States Global Change Research Program, 2020)

Efficacy

- "The extent to which the strategy, if successfully implemented, reduces the risk." (New York State Energy Research and Development Authority, 2020)

Elements at Risk

- "Population, buildings and engineering works, infrastructure, environmental features, and economic activities in the area affected by a hazard." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Emergency

- "Any occasion or instance for which, in the determination of the President, Federal assistance is needed to supplement State and local efforts to save lives and to protect property and public health and safety, or to lessen or avert the threat of a catastrophe in any part of the United States. The Governor of a State, or the Acting Governor in his/her absence, may request that the President declare an emergency when an incident occurs or threatens to occur in a State which would not qualify under the definition of a major disaster. Assistance authorized by an emergency declaration is limited to immediate and short-term assistance, and may not exceed $5 million, except when authorized by the FEMA Associate Director for Response and Recovery under certain conditions." (FEMA, 2001); cites Robert T Stafford Act 102; 44 CFR 206.2, 206.35; 206.63, 206.66, and 503.

Emergency Management

- "The process of preventing, preparing for, responding to, and recovering from an emergency; where an emergency is an unexpected, large-scale, damaging event." (Neudorff, Mason, & Bauer, 2012)
- The entire process of planning and intervention for rescue and relief to reduce the impact of emergencies as well as the response and recovery measures, to mitigate the significant social,

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economic, and environmental consequences to communities and ultimately to the country, usually through an emergency operation center, EOC. (Disaster and Emergency Reference Center, 1998)

– "Organized analysis, planning, decision-making, and assignment of available resources to mitigate (lessen the effect of or prevent) prepare for, respond to, and recover from the effects of all hazards. The goal of emergency management is to save lives, prevent injuries, and protect property and the environment if an emergency occurs." (FEMA, 1995)

– "The process through which America prepares for emergencies and disasters, responds to them, recovers from them, rebuilds, and mitigates their future effects." ((FEMA, 2001), citing FEMA Strategic Plan)

Emergency Response

– "A response to emergencies, including both natural disasters, e.g., hurricanes, floods, earthquakes, etc., and human-induced events, e.g., civil commotion, adversary attacks, etc., in order to protect lives and limit damage to property and impact on operations." (AWWA, 2014)

Equitable Access

– "The ability of the system to provide the opportunity for access across the entire community during a shock or stress and when the system is undisrupted." (Weilant, Strong, & Miller, 2019)

Event

– "Occurrence or change of a particular set of circumstances." (ISO, 2009)

Event Tree (also called "Failure Tree")

– "(also called "failure trees") – The sequence of events between the initiation of an event and the termination of the event is described as a branching tree, where each "branch" represents the possible outcomes at that junction (e.g., a locked door may be breached or not). The evaluation team estimates the probability of each outcome. Multiplying the probabilities along each branch, from the initiating event to each terminal event, calculates the probability of each unique branch, while all branches together sum to unity (1.0). The sum of the probabilities of all branches on which the attack succeeds is the vulnerability estimate." (AWWA, 2014)

Event Tree Analysis

– "An inductive analysis that utilizes a graphical "tree" construct to analyze the logical sequence of the occurrence of events in, or states of, a system following an initiating event (often called the "top event")." (AWWA, 2014)

Expert Elicitation

– "Using experts to provide information not readily available is often subjective or cannot be obtained from historical records. For example, members of the RAMCAP Plus evaluation team familiar with a facility's layout and work flows and knowledgeable about the asset being assessed discuss the

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likelihood of success of an attack of a particular type and provide logic and reasoning for their estimates. Sometimes trained facilitators, on staff or under contract, are used to elicit the judgments." (ASME, 2009)

Exposure

– "The nature and degree to which a system or asset is exposed to significant climate variations." (FHWA, 2015)

Extreme Events

– "Extreme events are not only [rare and] severe, but also outside the normal range of experience of the system in question." (Bier, Haimes, Lambert, Matalas, & Zimmerman, 1999)

– "An extreme event in the context of the natural world is an act of nature, "such as a lightning strike or a flood [that] may be a productive resource and a hazard at the same time. Lightning may kill an animal but also start a fire essential to the preservation of a forest ecosystem. A flood may destroy a farmstead while fertilizing the fields." (Burton, Kates, & White, 1993)

– "For the purposes of this directive, the term "extreme events" refers to risks posed by climate change and extreme weather events. The definition does not apply to other uses of the term nor includes consideration of risks to the transportation system from other natural hazards, accidents, or other human induced disruptions." (FHWA, 2014)

Extreme Weather Events

– "Weather events that can include significant anomalies in temperature, precipitation, and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires, and windstorms (including tornadoes and tropical storms). Consequences of extreme weather events can include safety concerns, damage, destruction, and/or economic loss. Climate change can also cause or influence extreme weather events." (Flannery, Pena, & Manns, 2018)

Facility

– "This term is commonly used to describe a fixed manufacturing or operating site or installation. However, the more general term "asset" as used in this document includes "facilities" as well as other types of assets. Assets may also be constituent elements of a facility." (AWWA, 2014).

Failure

– "Loss of ability to operate to specification, or to deliver the required output. The term failure may be used when referring to IT services, processes, activities, configuration items, etc. A failure often causes an incident." (DRI International, Inc., 2021)

– "The inability of a system, or part thereof, to function as intended. In the context of structural safety (including geotechnical structures), failure is generally confined to issues of structural integrity, and in some contexts to the special case of the collapse of the structure or some part of it." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

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Failure Mode

- “A way that failure can occur, described by the means or underlying physics by which element or component failures must occur to cause loss of the subsystem or system function.” (AWWA, 2014)

Fault Tree Analysis

- “A specific form of event tree (see above).” (ASME, 2009)
- “A deductive logic diagram that depicts how a particular undesired event can occur as a logical combination of other undesired events.” (AWWA, 2014)

Financial Plan

- “A long-term plan spanning 10 years or longer, presenting a State DOT's estimates of projected available financial resources and predicted expenditures in major asset categories that can be used to achieve State DOT targets for asset condition during the plan period, and highlighting how resources are expected to be allocated based on asset strategies, needs, shortfalls, and agency policies.” (FHWA, n.d.)

Feasibility

- “How practical it is for a particular strategy to be implemented by a department, accounting for engineering, policy, legal, and insurance considerations.” (New York State Energy Research and Development Authority, 2020)
- How practical it is for a particular strategy to be implemented by a department, accounting for engineering, policy, legal, and insurance considerations. (New York State Energy Research and Development Authority, 2020)

Frequency

- “The rate of occurrence of an event measured in terms of the number of a particular type of event expected to occur in a particular period of interest, usually one year, or in a particular number of iterations, e.g., one defect per million products.” (AWWA, 2014)
- “A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials (see also likelihood and probability).” (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Hazard

- “A condition, which may result from either an external cause (e.g., earthquake, flood, or human agency) or an internal vulnerability, with the potential to initiate a failure mode. It is a source of potential harm or loss.” (ASME, 2009)
- “An event or condition that may cause injury, illness, or death to people or damage to assets.” (United States Global Change Research Program, 2020)

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- "A dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. UNISDR Editor's Note: The hazards of concern to disaster risk reduction as stated in footnote 3 of the Hyogo Framework are "... hazards of natural origin and related environmental and technological hazards and risks." Such hazards arise from a variety of geological, meteorological, hydrological, oceanic, biological, and technological sources, sometimes acting in combination. In technical settings, hazards are described quantitatively by the likely frequency of occurrence of different intensities for different areas, as determined from historical data or scientific analysis." (United Nations Office for Disaster Risk Reduction (UNISDR) Terminology, 2016)
- "Something that is potentially dangerous or harmful, often the root cause of an unwanted outcome." (DHS, 2006)
- "Hazard means an event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, or other types of harm or loss." (FEMA, 1997)
- "Relevant to emergency preparedness, a hazard is an emergency or disaster resulting from a natural disaster, or an accidental or man-caused event." (FEMA, 2001), p. 58, citing Robert T. Stafford Act, 602)
- "A potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation." (UNISDR, 2002)

Hazard (Intentional)

- "Human actions with the intent to cause harm to other humans and what they value are termed intentional hazards. Today, terrorism is the source of most of the intentional hazards." (Dymon, 2004)

Hazard (Natural)

- "…those elements of the physical environment harmful to man and caused by forces extraneous to him." ((Smith, 1996) quoting (Burton, Kates, & White, 1993))

Hazard (Technological)

- "A range of hazards emanating from the manufacture, transportation, and use of such substances as radioactive materials, chemicals, explosives, flammables, agricultural pesticides, herbicides, and disease agents; oil spills on land, coastal waters, or inland water systems; and debris from space." (FEMA, 1992)

Hazard Analysis

- "Involves identifying all of the hazards that potentially threaten a jurisdiction and analyzing them in the context of the jurisdiction to determine the degree of threat that is posed by each." (FEMA, 1997)

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Hazard Assessment

- "Hazard assessments are simply a process of identifying hazards, evaluating the risks presented by those hazards, and managing the risks of the hazards of the experiment to be performed by incorporating appropriate hazard controls into the experimental design process." (Virginia Tech, 2011)

Human Factors

- "Human factors refer to environmental, organizational and job factors, and human and individual characteristics which influence behavior in a way which can affect safety." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Hazard Identification

- "…the process of defining and describing a hazard, including its physical characteristics, magnitude and severity, probability and frequency, causative factors, and locations/areas affected". (FEMA, 1997)
- "…the identification of potential sources of harm." (ISO, 1990)
- The process of recognizing that a hazard exists and defining its characteristics (Standards Australia/Standards New Zealand, 1995)

Incident

- "An occurrence or event, natural or human-caused, that requires an emergency response to protect life or property. Incidents can, for example, include major disasters, emergencies, terrorist attacks, terrorist threats, wildland, and urban fires, floods, hazardous materials spills, nuclear accidents, aircraft accidents, earthquakes, hurricanes, tornadoes, tropical storms, war-related disasters, public health and medical emergencies, and other occurrences requiring an emergency response." (DHS, 2006), p. 103.
- "Any condition that meets the definition of a major disaster or emergency which causes damage or hardship that may result in a Presidential declaration of a major disaster or an emergency." ((FEMA, 2001), citing Title 44 CFR 206.32)

Incident Analysis

- "A retrospective analysis of incidents at a particular site, among assets within a particular site, or assets within a category in a particular area, which indicates patterns of potential adversarial activities or intentions. Incident analyses should include an assessment of countermeasures sufficiency based on the ability to assess and respond to the suspicious activities in such a way as to reduce the likelihood of success if an actual attack occurred." (ASME, 2009)

Infrastructure

- "In transit systems, all the fixed components of the transit system, such as rights-of-way, tracks, signal equipment, stations, park-and-ride lots, but stops, maintenance facilities. 2) In transportation planning, all the relevant elements of the environment in which a transportation system operates. (TRB1) 3) A term connoting the physical underpinnings of society at large, including, but not limited

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to, roads, bridges, transit, waste systems, public housing, sidewalks, utility installations, parks, public buildings, and communications networks." (FHWA, 2017)

Initiating Event

– "An event that appears at the beginning of a chain of events or a sequence of events which, directly or indirectly, has the potential to cause harm or loss. Such events may include major disasters, emergencies, terrorist attacks, terrorist threats, wildland, and urban fires, floods, hazardous material spills, nuclear accidents, aircraft accidents, earthquakes, hurricanes, tornadoes, tropical storms, war- related disasters, public health and medical emergencies, and other occurrences requiring an emergency response." (AWWA, 2014)

Insider Threat

– "One or more individuals with the access and/or inside knowledge of a company, organization, or enterprise that would allow them to exploit the vulnerabilities of that entity's security, systems, services, products, or facilities with the intent to cause harm." (AWWA, 2014)

Intent

– "An adversary's goals and the value that the adversary would ascribe to achieving these goals through a particular means, as determined by expert judgment. In terrorism, the intent can be to inflict economic damage, mass fatalities, mass terror, symbolic goals, i.e., attacks against cultural symbols or against targets where there was a prior failure. This type of intent can be focused on types or categories of assets as targets (e.g., buses in Israel, or U.S. embassies) or with the demonstration of an adversary's capability (e.g., certain weapons of mass destruction)." (AWWA, 2014)

Intensity

– "…refers to the damage-generating attributes of a hazard. For example, water depth and velocity are commonly used measures of the intensity of a flood. For hurricanes, intensity typically is characterized by the Saffir/Simpson scale, which is based on wind velocity and storm surge depths…The absolute size of an earthquake is given by its Richter magnitude (and other similar magnitude scales), but its effects in specific locations are described by the Modified Mercalli Intensity (MMI) Scale…Earthquake intensity is also ascertained by physical measures such as peak ground acceleration (expressed as a decimal fraction of the force of gravity, e.g., 0.4 g), peak velocity, or spectral response, which characterizes the frequency of the energy content of the seismic wave." (Deyle, French, Olshansky, & Paterson, 1998)

Investment Strategy

– "A set of strategies that result from evaluating various levels of funding to achieve State DOT targets for asset condition and system performance effectiveness at a minimum practicable cost while managing risks." (FHWA, n.d.)

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Lane Mile

- "One continuous mile of highway that includes one single travel lane." (CDOT, 2020)

Level of Resilience (LOR)

- "Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood." (ISO, 2009)

Levels of Service (LOS)

- "A qualitative assessment of a road's operating conditions. For local government, comprehensive planning purposes, level of service means an indicator of the extent or degree of service provided b, or proposed to be provided by, a facility based on and related to the operational characteristics of the facility. Level of service indicates the capacity per unit of demand for each public facility. 2) This term refers to a standard measurement used by transportation officials which reflects the relative ease of traffic flow on a scale of A to F, with free-flow being rated LOS-A and congested conditions rated as LOS-F." (FHWA, 2017)

Life Cycle Cost

- "The total cost of a project or item over its useful life. This includes all of the relevant costs that occur throughout the life of a project or item, including initial acquisition costs (such as the right of way, planning, design, and construction), operation, maintenance, modification, replacement, demolition, financing, taxes, disposal, and salvage value as applicable." (WDOT, 2020)
- "In a pure asset management context, the term "life-cycle costs" includes all of the costs that an agency incurs in managing assets from the creation of the asset to its ultimate disposal." (AASHTO, 2013)

Life Cycle Planning and Management

- "A process to estimate the cost of managing an asset class, or asset sub-group over its whole life with consideration for minimizing cost while preserving or improving asset condition." (AASHTO, 2013)

Likelihood

- "The chance, frequency, or degree of belief that a particular outcome or event will occur in a specific time frame, usually one year." (ASME, 2009)
- "Chance of something happening, whether defined, measured or estimated objectively or subjectively. It can use general descriptors (such as rare, unlikely, likely, almost certain), frequencies, or mathematical probabilities. It can be expressed qualitatively or quantitatively." (DRI International, Inc., 2021)

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- "Conditional probability of an outcome given a set of data, assumptions, and information. Also used as a qualitative description of probability and frequency." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Loss Prevention

- "The set of activities undertaken to preclude or mitigate the effects of adverse impacts on assets due to natural and adversarial threats." (ASME, 2009)

Man-made (Anthropogenic/Human-Caused) Threats (Hazards)

- "A man-made hazard is a threat having an element of human intent, negligence, or error, or involving a failure of a man-made system." (Akpeninor, 2012).
- "Human caused hazards: these result from intention acts of humans and include terrorism, school and workplace violence, chemical attacks, and more." (The Polis Center, 2015)
- "Man-made (i.e., anthropogenic, or human-induced) hazards are defined as those "induced entirely or predominantly by human activities and choices". This term does not include the occurrence or risk of armed conflicts and other situations of social instability or tension which are subject to international humanitarian law and national legislation. Technological hazards are normally considered a subset of man-made hazards." (UNISDR, 2018)

Measurement

- "A measurement is the act or the process of measuring, where the value of a quantitative variable in comparison to a (standard) unit of measurement is determined. A measure is a variable to which a value is assigned as a result of the measurement. According to the Webster dictionary, a measure represents the dimensions, capacity, or amount of something." (ENISA, 2011)
- "An indicator of performance or condition." (FHWA, 2021)

Metric

- "Something that is measured and reported to help manage a process, IT service or activity." (DRI International, Inc., 2021)
- "A metric is a system of related measuring enabling quantification of some characteristic of a system, component, or process. A metric is composed of two or more measures. For example, the number of information security incidents per day is a security metric. The metric represents the incident rate, which is related to the "security" attribute of a system,the in function of time. The composing measures are 3 incidents and 1 day." (ENISA, 2011)

Minimum Practical Cost

- "Lowest feasible cost to achieve the objective." (FHWA, n.d.)

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Mitigation

- "Activities designed to reduce or eliminate risks to persons or property or to lessen the actual or potential effects or consequences of an incident. Mitigation measures may be implemented prior to, during, or after an incident. Mitigation measures are often developed in accordance with lessons learned from prior incidents. Mitigation involves ongoing actions to reduce exposure to, probability of, or potential loss from hazards. Measures may include zoning and building codes, floodplain buyouts, and analysis of hazard-related data to determine where it is safe to build or locate temporary facilities. Mitigation can include efforts to educate governments, businesses, and the public on measures they can take to reduce loss and injury." (DHS, 2019)
- "…sustained action taken to reduce or eliminate long-term risk to people and property from hazards and their effects. Mitigation distinguishes actions that have a long-term impact from those that are more closely associated with preparedness for, immediate response to, and short-term recovery from a specific event" (FEMA, 1997).
- "Any action taken to eliminate or reduce the long-term risk to human life and property from natural hazards. Mitigation actions are accomplished by:
    - **Acting on the hazard.** Seeding hurricanes or triggering avalanches may eliminate a hazard before a disaster occurs.
    - **Redirecting the hazard.** A seawall or dune restoration program helps keep water away from people by redirecting the impact areas away from vulnerable locations.
    - **Interacting with the hazard.** Seismic safety provisions incorporated into building codes result in structures that are more able to withstand impacts and earthquakes.
    - **Avoiding the hazard.** "River corridor projects create multiple beneficial uses of the floodplain while relocating structures to less vulnerable locations." (FEMA, 1999)
- "Processes that can reduce the amount and speed of future climate change by reducing emissions of heat-trapping gases or removing them from the atmosphere." (United States Global Change Research Program, 2020)
- "Activities taken to reduce the impacts from hazards." (DRI International, Inc., 2021)
- "Measures undertaken to limit the adverse impact of, for instance, natural hazards, environmental degradation, and technological hazards." (DRI International, Inc., 2021)
- "The act of alleviating a harmful circumstance. Risk mitigation seeks to reduce the probability and/or impact of a risk to below an acceptable threshold." (California Department of Transportation, 2003)
- "Structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation, and technological hazards." (UNISDR, 2002)

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Mobility

- "The ability to move or be moved from place to place." (FHWA, 2017)
- "Mobility is considered to be one of the primary justifications for having a transportation network. A common way of measuring mobility, using a broad definition of it, is origin-destination (O-D) travel time. Transportation planners compute O-D travel times by link, trip purpose, time of day, and season as a part of facility planning. This usually provides sufficient detail for asset management purposes. As a means of tracking agency performance for public consumption, a single network average trip time on a particular class of road is usually sufficient. Senior management will typically want more detail, such as peak hour trip times by corridor, as a way of identifying emerging needs for new capacity." (AASHTO, 2013)

Monte Carlo Simulation/Analysis/Method

- "Computerized probabilistic calculations that use random number generators to draw samples from a probability distribution." (Ashley, Dickmann, & Molenaar, 2006)
- "A procedure, which seeks to simulate stochastic processes by random selection of input values to an analysis model in proportion to their joint probability density function." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Natural Events/Hazards/Threats

- "These include floods, snowstorms, extreme wind, wildfire, landslide, tsunami, and earthquake. While probabilities and return periods of these events may be understood, it cannot be predicted when exactly the next event will occur. These events cannot be controlled, although an agency can prepare and mitigate against the effects in advance." (AASHTO, 2013)

Net Benefits

- "Gross benefits less costs (see which), where costs include the present value of an investment and operating costs (also known as "life-cycle" costs); a measure of value." (AWWA, 2014)

Operational Costs

- "Sometimes referred to as revenue or running costs, these are the costs resulting from day-to-day running of an operation (e.g., staff costs, hardware maintenance, and electricity)." (ISIXSIGMA, n.d.)
- "Operating costs are associated with the maintenance and administration of a business on a day-to-day basis. Operating costs include direct costs of goods sold (COGS) and other operating expenses—often called selling, general, and administrative (SG&A)—which includes rent, payroll, and other overhead costs, as well as raw materials and maintenance expenses. Operating costs exclude non-operating expenses related to financing such as interest, investments, or foreign currency translation." (Murphy, 2020)

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Operational Risk

- "The risk of loss resulting from inadequate or failed procedures and controls. This includes loss from events related to technology and infrastructure, failure, business interruptions, staff related problems, and from external events such as regulatory changes." (DRI International, Inc., 2021)

Owner Costs

- "Owner costs are the replacement value of each asset and may include the asset life-cycle cost in more comprehensive Risk and Resilience (R&R) analyses." (Kemp, Flannery, & Krimmer, 2017)

Performance Indicators ("Key Performance Indicators")

- "Key Performance Indicators are a set of quantifiable measures that an organization uses to gauge its performance and determine if it is meeting its strategic and operational goals." (PierceTransit, 2021)
- "Key performance indicators typically include, but are not limited to, elements such as project benchmarks, targets, milestone dates, numbers, percentages, variances, distributions, rates, time, cost, indexes, ratios, survey data, and report data." (Molenaar & Navarro, 2011)

Performance Measurement

- "A process of assessing progress toward achieving predetermined goals." (Neudorff, Mason, & Bauer, 2012)

Performance Measure

- "A measurable result related to either quantitative or qualitative answers." (CDOT, 2020)
- "Performance measures are quantifiable indicators of performance that can be used to evaluate progress toward achievement of a goal or objective. While often used interchangeably with "indicator," performance measures generally denote the presence of specific quantification mechanisms, units, and implied targets/benchmarks." (Zeitman & Ramani, 2011)
- "Indicators of how well the transportation system is performing with regard to such things as average speed, reliability of travel, and accident rates. Used as feedback in the decision-making process." (FHWA, 2017)
- "Performance measures are defined as indicators of system effectiveness and efficiency." (Amekudzi & Meyer, 2011)
- "In an asset management context, reliability is closely related to mobility and is defined as the standard deviation of origin-destination travel time. This definition is used because it is compatible with all types of modes and system components. Reliability can be improved by adding capacity, by responding more effectively to incidents, and by improving system operations management."
- "Indicators that provide the basis for evaluating the transportation system operating conditions and identifying the location and severity of congestion and other problems." (Neudorff, Mason, & Bauer, 2012)

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Performance Metrics

- "Performance metrics are defined as figures and data representative of an organization's actions, abilities, and overall quality. There are many different forms of performance metrics, including sales, profit, return on investment, customer happiness, customer reviews, personal reviews, overall quality, and reputation in a marketplace. Performance metrics can vary considerably when viewed through different industries." (ASQ, 2021)

Preparedness

- "Actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change related damages to life, health, property, livelihoods, ecosystems, and national security." (FHWA, 2014)
- "The range of deliberate critical tasks and activities necessary to build, sustain, and improve the operational capability to prevent, protect against, respond to, and recover from domestic incidents. Preparedness is a continuous process involving efforts at all levels of government and between government and private sector and nongovernmental organizations to identify threats, determine vulnerabilities, and identify required activities and resources to mitigate risk." (DHS, 2006)
- "Those activities, programs, and systems that exist prior to an emergency that is used to support and enhance response to an emergency or disaster." (FEMA, 1992)
- "The term 'preparedness' refers to the existence of plans, procedures, policies, training, and equipment necessary at the Federal, State, and local level to maximize the ability to prevent, respond to, and recover from major events. The term 'readiness' is used interchangeably with preparedness." (HSPD-8 (Homeland Security Presidential Directive), 2003)

Prevention

- "Activities to provide outright avoidance of the adverse impact of hazards and related environmental, technological and biological disasters." (UNISDR, 2002)

Preventative Measures

- "Performance measurement is the use of evidence to determine progress toward specific defined organizational objectives. This includes both quantitative evidence (such as the measurement of customer travel times) and qualitative evidence (such as the measurement of customer satisfaction and customer perceptions)." (FHWA, 2017)

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Priority Access

- “The resilience of a critical infrastructure asset could also be enhanced by giving it priority access to critical resources, thereby maintaining its services, or getting services back on-line more quickly to aid in a more general community recovery.” (AASHTO, 2017)

Probability (also look at Likelihood)

- “A quantitative measure of the likelihood that a particular event, i.e., terrorist attack or natural event, will occur. This is usually expressed as a mean value between 0 and 1 and can include a minimum and maximum range or distribution (density function). However, probability can also be expressed in qualitative terms (e.g., low, moderate, high) if there is a common understanding of the qualitative terms among all the stakeholders. The probability must be associated with a specific event and either a defined time frame (e.g., range of probability that a threat occurs in one year) or sa et of trials (e.g., range of probability of detecting a particular type of intrusion given 10 attempts or range of probability that a consequence mitigation action is successful given a demand).” (ASME, 2009).
- “A measure of the likelihood, degree of belief, frequency, or chance that a particular event will occur in a period of time (usually one year) or a number of iterations or trials. This is usually expressed quantitatively as a value between 0 and 1, a range of values between 0 and 1, a distribution (density function), or the mean of such a distribution. Probability can also be expressed in qualitative terms, e.g., low, moderate, or high, if there is a common understanding of the meaning of the qualitative terms.” (AWWA, 2014)
- “The likelihood of hazard events occurring. Probabilities have traditionally been determined from the historic frequency of events. With changing climate and the introduction of non-climate stressors, the probability of hazard events also changes.” (United States Global Change Research Program, 2020)

Probabilistic Model

- “A probability model is a mathematical representation of a random phenomenon. It is defined by its sample space, events within the sample space, and probabilities associated with each event.” (Yale University, 1998)

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- "Model with inputs that are quantities or probability distributions and with outputs that are probability distributions. Model logic attempts to adhere to laws of probability." (PHMSA, 2020)

Projection

- "A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models." (International Panel on Climate Change, 2018)

Protection

- "Actions to mitigate the overall risk to CI/KR assets, systems, networks, or their interconnecting links resulting from exposure, injury, destruction, incapacitation, or exploitation. In the context of the NIPP, protection includes actions to deter the threat, mitigate vulnerabilities, or minimize consequences associated with a terrorist attack or other incident. Protection can include a wide range of activities, such as hardening facilities, building resiliency and redundancy, incorporating hazard resistance into initial facility design, initiating active or passive countermeasures, installing security systems, promoting workforce surety, and implementing cyber security measures, among various others." (DHS, 2006)

Qualitative

- "Concepts that cannot be communicated through a natural metric, such as national security consequences or judgments of potential interactions between adaptive humans. Such concepts must sometimes be stated descriptively and specifically, but wherever possible should be couched in a measure that allows comparisons. Qualitative measures can be linguistic (e.g., high, medium, low) or quantified (e.g., a scale of 1 to 10)." (ASME, 2009)

Qualitative Risk Analysis/Assessment

- "An appraisal of risk that uses linguistic terms and measurements to characterize the factors of risk. Wherever possible, qualitative analyses should be couched in terms of a consistent measure that allows comparisons between assets. Qualitative measures can be linguistic, e.g., high, medium, low, or quantified, e.g., a scale of 1 to 10." (AWWA, 2014)
- "An analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Quantified

- "A quantitative measure that uses numbers as a proxy for language. This enables greater precision in the communication of items that fall within ranges and facilitates the use of mathematics to calculate decision-relevant terms (e.g., risk, risk reduction, resilience, and benefit-cost ratio)." (ASME, 2009)

Quantify

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- "To apply numerical ratings to things that do not have natural metrics, such as threat and vulnerability." (ASME, 2009)

Quantitative

- "Concepts that are easily communicated through a natural metric, such as numbers of lives, dollars, frequency, etc." (ASME, 2009)

Quantitative Risk Analysis/Assessment

- "An analysis based on numerical values of the probability, vulnerability, and consequences, and resulting in a numerical value of the risk." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)
- An appraisal of risk that uses numerical measures to describe factors in the analysis. Wherever possible, quantitative measures should be used to allow clear, defensible, and precise comparisons among assets." (ASME, 2009)

Radiative Forcing

- "A measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. It is used to assess and compare the anthropogenic and natural drivers of climate change." (FHWA, 2020)

RAMCAP™ Plus

- "An all-hazard risk and resilience management process for critical infrastructure." (ASME, 2009)

Rapidity

- "The capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption." (Bruneau, et al., 2003)

Recovery

- "Activities and programs designed to return conditions to a level that is acceptable to the entity." (DRI International, Inc., 2021)
- " The development, coordination, and execution of service- and site-restoration plans for impacted communities and the reconstitution of government operations and services through individual, private sector, nongovernmental, and public assistance programs that identify needs and define resources; provide housing and promote restoration; address long-term care and treatment of affected persons; implement additional measures and techniques, as feasible; evaluate the incident to identify lessons learned; and develop initiatives to mitigate the effects of future incidents." (DHS, 2006)
- "Those long-term activities and programs beyond the initial crisis period of an emergency or disaster and designed to return all systems to normal status or to reconstitute these systems to a new condition that is less vulnerable." (FEMA, 1992)

Redundancy

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- “Redundancies to the asset or system can improve resilience by being able to reroute production or process flows through one or more parallel components or subsystems.” (AASHTO, 2017)

- “Defined as duplicative or excess capacity that can be used in times of emergency. adding redundant highway capacity generally falls outside the practice of asset management. However, sound management of the assets on a detour and emergency evacuation routes increases a highway system’s redundancy.” (FHWA, 2013)
- “The state of having duplicate capabilities, such as systems, equipment, or resources.” (DRI International, Inc., 2021)

Reference Threat

- “A particular attack, specified in terms of intensity or magnitude, mode, and medium of delivery, to be usedconsistentlyn across numerous assets to facilitate direct comparisons. It is not to be confused with “design basis threat,” which is the type and intensity of threat a facility is designed to withstand.” (ASME, 2009)

Reliability

- “Likelihood of successful performance of a given project element. Mathematically, Reliability = 1 - Probability of failure. See definitions of “probability” and “failure” (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004).

Remediation

- “The act of mitigating a vulnerability or a threat.” (DRI International, Inc., 2021)

Residual Risk

- “The amount of risk remaining after the net effect of risk reduction actions are taken. The residual reflects the impact of threats not deterred, consequences not avoided, and vulnerabilities not reduced through other countermeasures. The concept can also include the risks from threats not included in a risk analysis.” (ASME, 2009)
- “The level of risk remaining after all cost-effective actions have been taken to lessen the impact, probability and consequences of a specific risk or group of risks, subject to an organization’s risk appetite.” (DRI International, Inc., 2021).
- “The remaining level of risk at any time before, during, and after a program of risk mitigation measures has been taken.” (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Resilience

- “…a dictionary definition [Merriam-Webster Online Dictionary] for ‘resilience’ is: ‘an ability to recover from or adjust easily to misfortune or change’. Strategies based on resilience accept that efforts to prevent attacks (reduce threats) and to defend against those attacks (reduce vulnerabilities), albeit necessary, will inevitably prove insufficient. Strategies based on resilience address all three components of the risk equation in an integrated fashion.” (Critical Infrastructure Task Force, 2006)

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- "The capability to maintain function during an event or to recover function rapidly after an event, including the provision of a substitute function or asset provided after an attack or natural event. The concept of resilience is still being formalized, but candidate indicators include reductions in the duration and severity of service denial and/or economic losses to the community due to service denial." (ASME, 2009)
- "The ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions," and also, "The ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance." (AASHTO, 2017)
- "The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events." (AASHTO, 2017)
- "The capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption." (United States Global Change Research Program, 2020)
- "Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions." (FHWA, 2014)
- "...the ability to minimize the costs of a disaster, to return to a state as good as or better than the status quo ante, and to do so in the shortest feasible time." (Gilbert, 2010)

Resilience Management

- "The deliberate process of understanding resilience as both a function of loss of infrastructure components and the ability of the community to cope with the loss and recover in the shortest practical time. Resilience management includes the ability to model the interdependencies of infrastructure components and decide upon and implement actions that will increase the resilience of the community given the loss of a subset of infrastructure." (AWWA, 2014)

Resilience Metrics

- "Resilience is a measure to guarantee an acceptable level of service in the face of these challenges. Resilience metrics may be used to quantify how well a network can retain this level of service regarding different challenges." (Zieglmeier, 2016)

Resource Allocation

- "Is the process of assigning scarce resources to investments in transportation assets. The assigned resources can be money, staff time, contractor capacity, equipment, or other organizational requirements for assets. The investments can be capital projects, maintenance efforts, or other projects and activities that require the use of an organization's resources through various delivery methods." (ASME, 2009)

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Response

- “The reactive use of emergency response capabilities to deal with the immediate consequences of an incident or attack. Often used in conjunction with proactive measures to create a more comprehensive and holistic protection system.” (ASME, 2009)
- “Those activities and programs designed to address the immediate and short-term effects of the onset of an emergency or disaster.” (FEMA, 1992)

Restorative Capacity

- “The ability of the system to recover quickly after a shock or stress to normal functioning.” (Weilant, Strong, & Miller, 2019)

Return on Investment (ROI)

- “A measurement of the expected benefit of an investment. In the simplest sense it is the net profit of an investment divided by the net worth of the assets invested.” (DRI International, Inc., 2021)

Risk

- “The potential for loss or harm due to the likelihood of an unwanted event and its adverse consequences. It is measured as the combination of the probability and consequences of an adverse event. When the probability and consequences are expressed as numerical point estimates, the expected risk is computed as the product of those values. In the case of the RAMCAP Plus process and many other risk and resilience processes, the risk is the product of threat (likelihood or frequency of the event occurring), vulnerabilithe ty (likelihood that the event will cause the estimated consequences, given that the event occurs), and consequence.” (ASME, 2009)
- “A function of consequences, hazard frequency or likelihood, and vulnerability, which with point estimates, is the product of the terms. It is the expected value of the consequences of an initiating event weighted by the likelihood of the event’s occurrence and the likelihood that the event will result in the consequences, given that it occurs. Risk is based on identified events or event scenarios.” (AWWA, 2014)
- “The potential total cost if something of value is damaged or lost, considered together with the likelihood of that loss occurring. Risk is often evaluated as the probability of a hazard occurring multiplied by the consequence that would result if it did happen.” (United States Global Change Research Program, 2020)
- “A possible event that could cause harm or loss or affect the ability to achieve objectives. Risk is measured by the probability of a threat, the vulnerability of the asset to that threat, and the impact it would have if it occurred.” (DRI International, Inc., 2021)
- “The potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and associated consequences.” (AASHTO, 2017)
- “…the three components of risk: threat, vulnerability, and consequence.” (Critical Infrastructure Task Force, 2006)

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- "Risk is generally defined as the combination of the frequency of occurrence, vulnerability, and the consequence of a specified hazardous event." (DHS, 2019)
- "A measure of potential harm that encompasses threat, vulnerability, and consequence. In the context of the NIPP, the risk is the expected magnitude of loss due to a terrorist attack, natural disaster,another incidentdent, along with the likelihood of such an event occurring and causing that loss." (DHS, 2006)
- "The estimated impact that a hazard would have on people, services, facilities, and structures in a community; the likelihood of a hazard event resulting in an adverse condition that causes injury or damage. Risk is often expressed in relative terms such as a high, moderate, or low likelihood of sustaining damage above a particular threshold due to a specific type of hazard event. It also can be expressed in terms of potential monetary losses associated with the intensity of the hazard." (FEMA, 2001)
- "Risk is the threat to transportation operations caused by extreme events, other external hazards, and from asset, failure arising from any cause. Some examples of causes of asset failure are poor condition, unexpected loading, or poor work practices." (AASHTO, 2013)

Risk Allocation

- "Placing responsibility for a risk to a party through a contract. The fundamental tenets of risk allocation include allocating risks to the party best able to manage them, allocating risks in alignment with project goals, and allocating risks to promote team alignment with customer-oriented performance goals." (Ashley, Dickmann, & Molenaar, 2006)

Risk Assessment

- "The technical and scientific activity of estimating the components of risk and combining them into the estimate of risk. Risk analysis provides the processes for identifying hazards or hazard scenarios, event-probability estimation, vulnerability assessment, and consequence estimation. The risk analysis process answers three basic questions: (1) What can go wrong and how can it happen? (2) What is the likelihood that it will go wrong? (3) What are the consequences if it does go wrong? Risk analysis often includes estimating the impact of changes to a system to reduce risks by reducing the likelihood ofan attack, the vulnerability to attack, and/or the magnitude or duration of consequences given a successful attack. Reductions in risk due to such changes are the benefits of those changes. Risk analysis generally contains the following steps: scope definition, hazard identification, risk estimation, risk-reduction option evalua,tion and communication of information useful in risk management resource allocation." (AWWA, 2014)
- "The use of available information to estimate the risk to individuals or populations, property, or the environment, from hazards. Risk analyses generally contain the following steps: definition of scope, danger (threat) identification, estimation of the probability of occurrence to estimate hazard, evaluation of the vulnerability of the element(s) at risk, consequence identification, and risk estimation. Consistent with the common dictionary definition of analysis, viz. "A detailed examination of anything complex made in order to understand its nature or to determine its essential features", risk analysis involves the disaggregation or decomposition of the system and sources of risk into their

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fundamental parts." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

- "Risk assessment is the process of measuring the potential loss of life, personal injury, economic injury, and property damage resulting from natural hazards by assessing the vulnerability of people, buildings, and infrastructure to natural hazards.

  A risk assessment tells you:

  - "The hazards to which your state or community is susceptible;
  - What these hazards can do to physical, social, and economic assets;
  - Which areas are most vulnerable to damage from these hazards; and
  - The resulting cost of damages or costs avoided through future mitigation projects." (FEMA, 2001), iii.

- "A process to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability/capacity that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend." (UNISDR, 2002)
- The quantification of threats to an organization and the probability of them being realized (DRI International, Inc., 2021).

Risk Aversion

- **"**The behavior of humans while exposed to uncertainty to attempt to reduce that uncertainty." (Wikipedia, 2021)

Risk Characterization

- "Risk characterization is a synthesis and summary of information about a potentially hazardous situation that addresses the needs and interests of decision makers and interested and affected parties. Risk characterization is a prelude to decision making and depends on an interactive, analytical-deliberate process." (National Research Council, 1996), p. 27
- "…risk communication: the effective understanding of risks and the transfer of risk information to the public, and the transfer of information from the public to decisionmakers….Risk management decisions should not simply be made by technical experts and public officials and then imposed on and justified to, the public after the fact. Risk Communication involves a dialogue among interested parties – risk experts, policy makers, and affected citizens." (Committee on Risk-Based Analysis for Flood Damage Reduction, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Research Council, 2000)
- "…an interactive process of exchange of information and opinion among individuals, groups, and institutions….We construe risk communication to be successful to the extent that it raises the level of understanding of relevant issues or actions for those involved and satisfies them that they are adequately informed within the limits of available knowledge." (National Research Council, 1996)

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" (National Research Council, 1996) concludes that four objectives are key to improving risk communications: (1) goal setting, (2) openness, (3) balance, and (4) competence. As a means of achieving these objectives, it is important, at the start of any given project, to determine:

- What the public knows, believe, and does not believe about the subject risk and ways to control it;
- what quantitative and qualitative information do participants need to know to make critical decisions;
- and how they think about and conceptualize the risk (National Research Council, 1996)." (Pearce, 2000: HIRV)

Risk Communication

– "An interactive exchange of information and opinion among stakeholders designed to convey an understanding of risks and risk-reduction options to support resource allocation and other decisions to manage risks. It often involves multiple exchanges about the nature of risk and expressing concerns, opinions, or reactions of risk managers, legal experts, and management. Risk communication greatly affects risk acceptance, safety and security standards and the allocation of resources to risk reduction." (ASME, 2009)

Risk Management

– "The deliberate, cyclical process of understanding risk based on risk analysis and deciding upon, implementing, and managing action, e.g., security countermeasures or consequence mitigation features, to achieve an acceptable level of risk at an acceptable cost. Risk management is characterized by identifying, measuring, estimating, and controlling risks to a level commensurate with an assigned or accepted value, monitoring and evaluating the effectiveness of implementation and operation of the selected options (with corrective actions as needed) and periodic repetition of the full risk management cycle." (AWWA, 2014)

Risk Management Plan

– "Scheme within the risk management framework specifying the approach, the management components, and resources to be applied to the management of risk." (ISO, 2009)

– "Documents how the risk processes will be carried out during the project. This is the output of risk management planning." (Project Management Institute, 2004)

Risk Mitigation

– "The deliberate process of setting security and resilience goals; identifying assets, systems, networks, and functions; understanding risk; and deciding upon and implementing action (e.g., defining security countermeasures, consequence mitigation features or characteristics of the asset) to achieve an acceptable level of risk and resilience at an acceptable cost. Risk management identifies, estimates and controls risks to a level commensurate with an assigned or accepted value; it also measures performance and takes corrective action. Public and private sector entities often include risk management frameworks in their business continuity plans." (ASME, 2009)

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Risk Register

- "A document detailing all identified risks, including description, cause, probability of occurrence, impact(s) on objectives, proposed responses, owners, and current status." (Project Management Institute, 2004)

Risk Tolerance

- "Organization's readiness to bear the risk after risk treatments in order to achieve its objectives." (DRI International, Inc., 2021)

Risk Transfer/Transference

- "A common technique used by risk managers to address or mitigate potential exposures of the organization. A series of techniques describing the various means of addressing risk through insurance and similar products." (DRI International, Inc., 2021)

Road Weather Management

- "Mitigation strategies employed in response to various weather threats including fog, high winds, snow, rain, ice, flooding, tornadoes, hurricanes, and avalanches." (Neudorff, Mason, & Bauer, 2012)

Robustness

- "Defined as the capacity to cope with stress or uncertainty. asset management focuses upon optimizing the conditions of assets with available revenues. Well-maintained assets generally are better able to withstand the stresses of storm events and other disasters better than weakened and poorly maintained ones." (U.S. Department of Transportation, 2017)

Safety

- "The number of accidents, by severity, expected to occur on the entity per unit of time. An entity may be a signalized intersection, a road segment, a driver, a fleet of trucks, etc." (AASHTO, 2009)

Scenario

- "A combination of events and system states that lead to an outcome of interest. A scenario defines a suite of circumstances of interest in a risk assessment. In the present context, a scenario includes at least a specific attack threat on a specific asset, with the associated probabilities and consequences." (ASME, 2009)
- "A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but are useful to provide a view of the implications of developments and actions." (International Panel on Climate Change, 2018)

Scenario Planning

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- "Scenario planning provides a framework for developing a shared vision for the future by analyzing various forces (e.g., climate change, land use, economy) that affect growth and management of the transportation system. Scenario planning tests various future alternatives in order to identify solutions that meet state and community needs under a variety of potential futures. Scenario planning is used in exercises to make critical decisions in the face of uncertainty." (FHWA, 2017)

Sensitivity

- "The degree to which a transportation system or asset is affected by climate variability or change." (FHWA, 2015)
- "Refers to how an asset or system responds to, or is affected by, exposure to a climate change stressor. A highly sensitive asset will experience a large degree of impact if the climate varies even a small amount, where as a less sensitive asset could withstand high levels of climate variation before exhibiting any response." (FHWA, 2020)
- "The degree to which a system, population, or resource is or might be affected by hazards." (United States Global Change Research Program, 2020)

Severity

- "The amount of daily service denied." (AWWA, 2014)

Stakeholder

- "Individual or group having an interest in the performance or success of an organization e.g., customers, partners, employees, shareholders, owners, the local community, first responders, government, and regulators." (DRI International, Inc., 2021)
- "Person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity." (ISO, 2009)

Standards-Based Approach

- "The traditional approach to engineering, in which risks are controlled by following established rules as to design events and loads, structural capacity, safety coefficients and defensive design measures." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

State of Good Repair (SGR)

- "Refers to a condition in which existing physical assets, both individually and as a system, are functioning as designed within their useful service life and are kept functional through regular maintenance and replacement programs." (AASHTO, 2013)

Sustainability

- "Sustainability entails meeting human needs for the present and future while preserving environmental and ecological systems, improving quality of life, promoting economic development,

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and ensuring equity between and among population groups and over generations." (Zeitman & Ramani, 2011)

- "The capacity to endure. The goal of sustainability can be described with the triple bottom line, which includes considering three primary principles: social, environmental, and economic." (Flannery, Pena, & Manns, 2018)

System

- "An integrated combination of people, property, environment, and processes integrated to work in a coordinated manner to achieve a specific desired output under specific conditions. As used in this document, a system encompasses the set of one or more assets and their associated environment (e.g., threats, vulnerabilities, consequences, buffer zone attributes) considered in a risk analysis. Systems should be defined based on the decision-specific analytical objectives, which may lead to different types of definitions, such as "functional systems," "management systems," and "engineering systems." (FHWA, 2017)
- "A group of interacting, interrelated, or interdependent elements, such as people, property, materials, environment, and/or processes, for a single purpose or defined set of purposes. The elements together form a complex whole that can be a physical structure, process, or procedure of some attributes of interest." (AWWA, 2014)

Target

- See Asset (AWWA, 2014)

Technological Hazards

- "Technological hazards: These result from accidents or failures of systems and structures and include dam failures, hazardous materials spills, power failure, and more." (The Polis Center, 2015)

Threat

- "Any indication, circumstance, or event with the potential to cause the loss of, or damage to, an asset or population. In the case of terrorism risk, threat represents intention and capability of an adversary to undertake actions detrimental to an asset or population and also the attractiveness of the asset or population relative to alternative assets or populations. In the case of natural hazards, threat refers to the historical frequency of the specific natural event to which the asset(s) may be subjected. In both cases, for risk analysis, threat is defined as the likelihood the event will occur." (ASME, 2009)
- "Potential cause of an unwanted incident, which may result in harm to individuals, assets, a system or organization, the environment, or the community." (DRI International, Inc., 2021)
- "A man-made or natural event with the potential to cause harm. In malevolent risk analysis, threat is based on the analysis of the intention and capability of an adversary (whether insider or outsider) to undertake actions that would be detrimental to an asset. Threats may also arise from natural

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hazards or dependency hazards (interruptions of supply chains or proximity to dangerous or hazardous sites).” (AWWA, 2014)

Threat Analysis/Assessment

- “A systematic process of estimating threat likelihood determined based on historical frequencies or predictions from scientific tools and expert opinion.” (CDOT, 2020)
- “The study or assessment of threats, including adversary capability, intent and incidents that may be indicators of adversary activities.” (ASME, 2009; AWWA, 2014)
- “Process of formally evaluating the degree of threat to an information system or enterprise and describing the nature of the threat.” (DRI International, Inc., 2021)
- “Normalized assessments of attractiveness in light of the high-level objectives of terrorists and intelligence-based assessments of adversary capabilities and intent.” (Flannery, Pena, & Manns, 2018)

Threat Characterization

- “The identification and description of reference threat scenarios in enough detail to estimate vulnerability and consequences.” (ASME, 2009)
- “Threat scenario identification and description in enough detail to estimate vulnerability and consequences.” (Flannery, Pena, & Manns, 2018)
- “Process to identify possible scenarios and describe in enough detail to estimate vulnerability and consequences.” (CDOT, 2020)

Threat Likelihood

- “The probability that an undesirable event will occur. With natural hazards, the threat likelihood is the historical frequency of similar events unless there is a belief that the future will differ from the past. With terrorist threats, the likelihood is a function of available intelligence, the objectives and capabilities of the terrorist, and the attractiveness, symbolic or fear-inducing value of the asset as a target. The terms “threat likelihood” and “threat probability” are used interchangeably in this publication.” (AWWA, 2014; ASME, 2009)
- “Probability that an event will occur.” (Colorado State)

Transportation Asset Management

- “A strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost.” (FHWA, 2020)
- “A strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for

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resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives." (AASHTO, 2013; Neudorff, Mason, & Bauer, 2012)

– "The coordinated activity of an organization to realize value from assets. Realization of value involves the balancing of costs, risks, opportunities, and performance benefits. Asset management enables an organization to examine the need for, and performance of, assets and asset systems at different levels. Additionally, it enables the application of analytical approaches towards managing an asset over the different stages of its life cycle (which can start with the conception of the need for the asset, through to its disposal, and includes the managing of any potential post disposal liabilities)." (ISO, 2009; AASHTO, 2021)

Transportation Management Center (TMC)

– "The hub of a transportation management and control system. The TMC brings together human and technological components from various agencies to perform a variety of functions." (Neudorff, Mason, & Bauer, 2012)

Transportation Systems Management and Operations (TSMO)

– "An integrated program to optimize the performance of existing infrastructure through the implementation of systems, services, and projects designed to preserve capacity and improve security, safety, and reliability of the transportation system." (Neudorff, Mason, & Bauer, 2012)

Twice Damaged Assets ("Repeatedly damaged facilities")

– "Repeatedly damaged facilities are roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to natural disasters or catastrophic failures resulting in emergencies declared by the Governor of the State or the President." (23 CFR 667.1).

Uncertainty

– "A measure of unpredictability or knowledge incompleteness. In quantitative risk assessment, uncertainty includes chance events, measurement and estimation error, and simple lack of knowledge about the models and parameter values used. Uncertainties can be expressed as levels of confidence, ranges, or probability distributions." (ASME, 2009)

– "A state of incomplete knowledge. Uncertainty about future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make." (United States Global Change Research Program, 2020)

– "Describes any situation without certainty, whether or not described by a probability distribution. Uncertainty is caused by natural variation and/or incomplete knowledge (lack of understanding or insufficient data). In the context of structural safety, uncertainty can be attributed to (i) aleatory uncertainty: inherent variability in natural properties and events, and (ii) epistemic uncertainty: incomplete knowledge of parameters and the relationships between input and output values." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

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User Costs

- "…vehicle running costs and lost wages." (Kemp, Flannery, & Krimmer, 2017)
- "Road User Costs in the work zone are added vehicle operating costs, delay costs, and crash costs to highway users resulting from construction, maintenance, or rehabilitation activity." (NJDOT, 2015)
- "Those costs realized by the users of a facility. In life cycle-cost analysis, user costs could take the form of delay costs or of changes in the vehicle operating costs associated with various alternatives." (TRB, 2004)

Vulnerability

- "The degree to which a transportation system or asset is susceptible to, and unable to cope with, adverse effects of climate change, variability, and extremes. Vulnerability is a function of exposure, sensitivity, and adaptive capacity." (FHWA, 2015)
- "Any weakness in an asset or infrastructure's design, implementation or operation that can be exploited by an adversary or can contribute to functional failure in a natural disaster. Such weaknesses can occur in building characteristics, equipment properties, personnel behavior, locations of people, equipment, and buildings or operational and personnel practices. In risk analysis, vulnerabilities are estimated using a variety of methods, but usually summarized as the probability that, given an attack or natural event, the estimated consequences will ensue, i.e., will cause the estimated damage." (ASME, 2009)
- "The degree to which a system is susceptible to, or unable to cope with adverse effects of climate change or extreme weather events. In the transportation context, climate change vulnerability is a function of a transportation system's exposure to climate effects, sensitivity to climate effects, and adaptive capacity." (FHWA, 2020)
- "An inherent state of a system (e.g., physical, technical, organizational, cultural) that can be exploited by an adversary or impacted by a natural hazard to cause harm or damage. Such weaknesses can occur in building characteristics, equipment properties, personnel behavior, locations of people, equipment, and buildings, or operational and personnel practices. Vulnerability is expressed as the likelihood of an event's having the estimated consequences, given that the event occurs." (AWWA, 2014)
- "A weakness in the design, implementation, or operation of an asset, system, or network that can be exploited by an adversary, or disrupted by a natural hazard or technological failure." (DHS, 2006), p. 105
- "A vulnerability assessment presents "the extent of injury and damage that may result from a hazard event of a given intensity in a given area. The vulnerability assessment should address impacts of hazard events on the existing and future built environment." (FEMA, 2001)
- "Degree of loss (from 0% to 100%) resulting from a potentially damaging phenomenon." (United Nations, Department of Humanitarian Affairs, 1992)

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- "The degree of loss to a given element or set of elements within the area." (Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms, 2004)

Vulnerability Assessment

- "A systematic examination of an asset's ability to withstand a specific threat using current security and emergency preparedness procedures and controls. A vulnerability assessment often suggests countermeasures, mitigation features, and other security improvements. A vulnerability analysis may be used to: compute the probability a particular attack will succeed; compute the probability of significant damage, destruction, or incapacitation of part or all of an asset resulting from a given threat; identify weaknesses that could be exploited and predict the effectiveness of additional security measures in protecting an asset from attack." (ASME, 2009)

Vulnerability Estimate

- "The conditional probability that an attack or natural event will cause specifically estimated consequences." (ASME, 2009).

Vulnerability Logic Diagrams (VLDs)

- "VLDs are used to illustrate the flow of events from the time an adversary approaches the facility to the terminal event in which the attack is foiled or succeeds, considering the obstacles and countermeasures that must be surmounted, with each terminal event associated with a specific vulnerability "bin." This is frequently complemented by time estimates for each segment and compared with an estimate of the reaction time of a counterforce once the attack has been detected. In many of the RAMCAP Sector-Specific Guidance documents, VLDs are prepared in advance as a heuristic to guide the team in making its assessment." (ASME, 2009)

Worst Reasonable Consequence

- "An operating assumption for estimating consequence values that utilizes the most severe but reasonable consequences for a specific adversarial threat but does not combine unlikely coincidences. It directly reflects the assumption that an adversary is knowledgeable about the asset to be attacked and adaptive given emergent conditions." (ASME, 2009; AWWA, 2014)

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Bibliography

U.S. Climate Change Science Program and the Subcommittee on Global Change Research. (2008). *SAP 4.7. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study*. Retrieved from https://www.globalchange.gov/browse/reports/sap-47-impacts-climate-change-and-variability-transportation-systems-and/

(2004). *Homeland Defense Journal, 2*(6).

AASHTO. (2009). *Highway Safety Manual - 1st Edition.* Washington, D.C.: American Association of State Highway and Transportation Officials.

AASHTO. (2013). *AASHTOTransportation Asset Management Guide, A Focus on Implementation.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration.

AASHTO. (2013). *Transportation Asset Management Guide - A focus on Implementation: Exceutive Summary.* AASHTO. Retrieved from https://www.fhwa.dot.gov/asset/pubs/hif13047.pdf

AASHTO. (2017). *Understanding Transportation Resilience: A 2016-2018 Roadmap for Security, Emergency Management, and Infrastructure Protection in Transportation Resilience.* Washington, D.C.: American Association of State highway and Transportation Officials.

AASHTO. (2021). *AASHTO TAM Guide*. Retrieved February 9, 2021, from https://www.tamguide.com/guide/

Akpeninor, J. O. (2012). *Modern Concepts of Security.* Bloomington, IN: Author House.

Amekudzi, A., & Meyer, M. (2011). *Best Practices in Selecting Performance Measures and Standards for Effective Asset Management.* Atlanta, GA: Georgia Department of Transportation.

Asam, S., Bhat, C., Dix, B., Bauer, J., & Gopalakrishna, D. (2015). *Climate Change Adaptation Guide for Transportation Systems Management, Operations and Maintenance.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration. Retrieved from http://www.dot.state.oh.us/Divisions/Operations/Traffic-Management/TSMO%20Docs/FHWA%20Climate%20Change%20Adaptation%20Guide%20for%20Transportation%20Systems%20Management%20Operations%20and%20Maintenance.pdf

Ashley, D. B., Dickmann, J. E., & Molenaar, K. R. (2006). *Guide to Risk Assessment and Allocation for Highway Construction Management.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration.

ASME. (2009). *All-hazards Risk and Resilience: Prioritizing Critical Infrastructure Using the RAMCAP Plus Approach.* New York: American Society of Mechanical Engineers.

ASQ. (2021). *WHAT ARE PERFORMANCE METRICS?* Retrieved February 10, 2021, from https://asq.org/quality-resources/metrics

Australian National Committee on Large Dams. (1994). *Guidelines on Risk Assessment.* Australia.

AutoQuiz: What is the Definition of a Design Standard? . (2021). (International Society of Automation) Retrieved February 9, 2021, from https://blog.isa.org/design-standards-definition

AWWA. (2014). *Risk and Resilience Management of Wastewater Systems Using the ASME-ITI RAMCAP Plus Methodology.* Washington, D.C.: American Waster Water Association.

Draft - Not for Distribution

Bier, M., Haimes, Y. Y., Lambert, J. H., Matalas, N. C., & Zimmerman, R. (1999). Risk Analysis. *19*(1), 83-94.

Blanchard, B. W. (2006, July 28). Appendix: Select Emergency Management-Related Terms and Definitions in Hazards, Disasters and the U.S. Emergency Management System: An Introduction. Emmitsburg, MD: FEMA. Retrieved February 11, 2021, from https://training.fema.gov/hiedu/aemrc/courses/coursesunderdev/hazdisusems.aspx

Bruneau, M., Chang, S. E., Eguchi, R. T., O'Rourke, T. D., Reihnorn, A. M., Shinozuka, M., . . . Winterfeldt, D. v. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra, 19*(4), 733-752.

Burton, I., Kates, R., & White, G. (1993). *The Environment as Hazard. 2nd ed.* New York: Guilford Press.

California Department of Transportation. (2003). *Project Risk Management Handbook.* Sacramento, CA: California Department of Transportation, Office of Project Management Process Improvement.

CDOT. (2020). *Colorado Department of Transportation risk and resilience procedure: A manual for calculating risk to CDOT assets from flooding, rockfall, and fire debris flow.* Retrieved from https://www.codot.gov/programs/planning/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf

Colorado State. (n.d.). *Probability.* Retrieved February 11, 2021, from https://www.math.colostate.edu/~freeman/m130/probability1.pdf

Committee on Risk-Based Analysis for Flood Damage Reduction, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Research Council. (2000). *Risk Analysis and Uncertainty in Flood Damage Reduction Studies.* Washington, D.C.: National Academies Press.

Critical Infrastructure Protection Act of 2001, Public Law 107-56, Sec. 1016(6). (n.d.).

Critical Infrastructure Task Force. (2006). *Report of the Critical Infrastructure Task Force.* Washington, D.C.: Homeland Security Advisory Council.

Deyle, R., French, S., Olshansky, R., & Paterson, R. (1998). Hazard Assessment: The Factual Basis for Planning Mitigation. In R. Burby (Ed.), *Cooperating with Nature.* Washington, D.C.: National Academy Press.

DHS. (2006). *National Infrastructure Protection Plan.* Washington, D.C.: Department of Homeland Security.

DHS. (2019). *A Guide to Critical Infrastructure Security and Resilience.* Washington, D.C.: U.S. Department of Homeland Security. Retrieved from https://www.cisa.gov/sites/default/files/publications/Guide-Critical-Infrastructure-Security-Resilience-110819-508v2.pdf

Disaster and Emergency Reference Center. (1998). *Disaster Management Glossary.* (K. Nimpuno, Ed.) Delft, The Netherlands: Disaster and Emergency Reference Center.

DRI International, Inc. (2021). *DRI International Glossary*. Retrieved February 8, 2021, from https://drii.org/resources/viewglossary

Dymon, U. J. (2004). Session 1, Introduction to and Evolution of Hazard Mapping and Modeling. In *Hazard Mapping and Modeling (Draft FEMA Emergency Management Higher Education Project College Course).* Emmitsburg, MD: Emergency Management Institute, FEMA/DHS.

Draft - Not for Distribution

ENISA. (2011). *Measurement Frameworks and Metrics for Resilient Networks and Services: Technical Report.* European Network and Information Security Agency.

FEMA. (1990). *Definitions of Terms (Instruction 500.2).* Washington, D.C.: Federal Emergency Management Administration.

FEMA. (1992). *Federal Response Plan with revisions. (FEMA Publication 229).*

FEMA. (1995). *Introduction to Emergency Management.* Emmitsburg, MD: Emergency Management Institute.

FEMA. (1997). *Multi-Hazard Identification and Assessment.* Washington, D.C.: FEMA.

FEMA. (1999). The Professional in Emergency Management (Independent Study IS-513). Emmitsburg, MD: Emergency Management Institute .

FEMA. (2001). *The Disaster Dictionary-Common Terms and Definitions Used in Disaster Operations (9071.1-JA Job Aid).* Washington, D.C.: FEMA.

FEMA. (2001). *Understanding Your Risks: Identifying Hazards and Estimating Losses (State and Local Mitigation Planning How-To Guide, FEMA 386-2).* Washington, D.C.: FEMA.

FHWA. (2002, June 1). *Creating an Effective Program to Advance Transportation System Management and Operations*. Retrieved from https://ops.fhwa.dot.gov/Publications/fhwahop12003/background.htm

FHWA. (2013). *Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets. Report 5: Managing External Threats Through Risk-Based Asset Management.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration.

FHWA. (2014, December 15). *FHWA Order 5520*. Retrieved from https://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm

FHWA. (2015). *Gulf Coast Study*. Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/index.cfm

FHWA. (2017, June 28). *FHWA Scenario Planning and Visualization in Transportation*. Retrieved from https://www.fhwa.dot.gov/planning/scenario_and_visualization/

FHWA. (2017, June 28). *Planning Glossary*. Retrieved February 9, 2021, from https://www.fhwa.dot.gov/Planning/glossary/glossary_listing.cfm

FHWA. (2020, May 15). *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance*. Retrieved December 4, 2020, from https://ops.fhwa.dot.gov/publications/fhwahop15026/ch3.htm#s3f

FHWA. (2021). *Transportation Performance Management Terms*. Retrieved February 10, 2021, from https://www.tpmtools.org/wp-content/uploads/2016/09/guidebook-final-appendix-c.pdf

FHWA. (n.d.). *23 CFR § 515.5 - Definitions*. (Legal Information Institute) Retrieved February 8, 2021, from https://www.law.cornell.edu/cfr/text/23/515.5

Flannery, A., Pena, M., & Manns, J. (2018). *Resilience in Transportation Planning, Engineering, Management, Policy, and Administration: A Synthesis of Highway Practice.* Washington, D.C.: Transportation Research Board.

Draft - Not for Distribution

Gilbert, S. W. (2010). *Disaster Resilience: A Guide to the Literature.* National Institute of Standard and Technology (NIST). Retrieved from https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=906887

Hayes, A. (2020, August 21). *Benefit-Cost Ratio (BCR)*. (Investopedia) Retrieved February 9, 2021, from https://www.investopedia.com/terms/b/bcr.asp

HSPD-8 (Homeland Security Presidential Directive). (2003). *National Preparedness.* Washington, D.C.: The White House.

International Panel on Climate Change. (2018, April 6). *IPCC Glossary*. Retrieved from https://www.ipcc.ch/report/sr15/glossary/

ISIXSIGMA. (n.d.). *Definition of Operational cost*. Retrieved February 9, 2021, from https://www.isixsigma.com/dictionary/operational-cost/#:~:text=Definition%20of%20Operational%20Cost%3A,used%20up%20(e.g.%2C%20consultancy)

ISO. (1990). *Guidelines for the Inclusion of Safety Aspects in Standards (ISO Guide 51).* Geneva: International Standards Organization.

ISO. (2009). *International Standard ISO 31000 - Risk Management, Principles and Guidelines.* Geneva: International Standards Organization.

Kemp, E., Flannery, A., & Krimmer, M. (2017). Risk and Resilience Analysis for Highway Assets. *Transportation Research Record: Journal of the Transportation Research Board, 2604*, 1-8.

Molenaar, K. R., & Navarro, D. (2011). Key Performance Indicators in Highway Design and Construction. *Journal of the Transportation Research Board, 2228*, 51-58.

Murphy, C. (2020, December 27). *Operating Cost*. (Investopedia) Retrieved February 9, 2021, from https://www.investopedia.com/terms/o/operating-cost.asp

Nakanishi, Y. J., & Auza, P. M. (2015). *FEMA and FHWA Emergency Relief Funds Reimbursements to State Departments of Transportation.* Washington, D.C.: National Academies Press.

National Research Council. (1996). *Improving Risk Communication.* Washington, D.C.: National Academies Press.

National Science and Technology Council (NTSC), Committee on the Environmental and Natural Resources, Subcommittee on Natural Disaster Reduction. (1996). *Natural Disaster Reduction: A Plan for the Future.* Washington, D.C.: U.S. Government Printing Office.

Neudorff, L. G., Mason, J., & Bauer, J. (2012). *Glossary of Regional Transportation Systems Management and Operations Terms.* Washington D.C.: Transportation Research Board.

New York State Energy Research and Development Authority. (2020). *Responding to Climate Change in New York State (ClimAID)*. Retrieved from https://www.nyserda.ny.gov/About/Publications/Research%20and%20Development%20Technical%20Reports/Environmental%20Research%20and%20Development%20Technical%20Reports/Response%20to%20Climate%20Change%20in%20New%20York

NJDOT. (2015). *Road User Cost Manual.* State of New Jersey Department of Transportation.

Draft - Not for Distribution

Pearce, L. (2000: HIRV). *an Integrated Approach for Community Hazard, Impact, Risk and Vulnerability Analysis.* University of British Columbia Doctoral Dissertation.

PHMSA. (2020). *Pipeline Risk Modeling Overview of Methods and Tools for Improved Implementation.* Washington, D.C.: U.S. DOT Pipeline Hazardous Materials Administration.

PierceTransit. (2021). *Key Performance Indicators*. Retrieved February 19, 2021, from https://www.piercetransit.org/PT-Key-Performance-Indicators/

Project Management Institute. (2004). *A Guide to Project Management Body of Knowledge (PMBOK Guide).* Newton Square, PA: Project Management Institute.

Public Law 114-94, Fixing America's Surface Transportation Act . (2015, December 4). Retrieved from https://www.govinfo.gov/app/details/PLAW-114publ94

Smith, K. (1996). *Environmental Hazards - Assessing Risk and Reducing Disaster. 2nd ed.* London and New York: Routledge.

Standards Australia/Standards New Zealand. (1995). *AS/NZS 4360 - Risk Management.* North Sydney, Australia.

Systematics, C. (2009). *NCHRP Report 632: An Asset-Management Framework for the Interstate Highway System.* Transportation Reserach Board (TRB). Retrieved from https://www.nap.edu/download/14233

Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms. (2004). *Risk Assessment - Glossary of Terms.* Retrieved February 8, 2021, from http://140.112.12.21/issmge/2004Glossary_Draft1.pdf

The Polis Center. (2015). *Threat and Hazard Identification and Risk Assessment (THIRA).* Indianpolis, IN: Allen County Department of Homeland Security.

Transportation Research Board. (n.d.). *Transportation Benefit-Cost Analysis*. Retrieved February 9, 2021, from http://bca.transportationeconomics.org/home

TRB. (2004). *Guide for Mechanistic Empirical Design of New and Rehabilitated Pavement Structures: Appendix A.* Washington, D.C.: Transportation Research Bureau.

U.S. Department of Transportation. (2017, January). *Resilience and Transportation Planning.* Retrieved December 6, 2020, from http://www.planhillsborough.org/wp-content/uploads/2017/03/Resilience-Tsp-Fact-Sheet.pdf#:~:text=January%202017%20FHWA-HEP-17-028%20RESILIENCE%20AND%20TRANSPORTATION%20PLANNING%20.,secure%20and%20resilient%20to%20a%20myriad%20of%20hazards.

UNISDR. (2002). *Living With Risk: A Global Review of Disaster Reduction Initiatives (preliminary version).* Geneva: United Nations, International Strategy for Disaster Reduction.

UNISDR. (2018). *Man-made and Technological Hazards: Practical Considerations for Addressing Man-made and Technological Hazards in Disaster Risk Reduction.* New York: United Nations.

United Nations Office for Disaster Risk Reduction (UNISDR) Terminology. (2016). *DRI International (DRI) Glossary for Resilience*. Retrieved January 20, 2020, from http://drii.org/resources/viewglossary

Draft - Not for Distribution

United Nations, Department of Humanitarian Affairs. (1992). *Internationally Agreed Glossary of Basic Terms Related to Disaster Management. (DNA/93/36).* Geneva: United Nations.

United States Global Change Research Program. (2020, January 7). *U.S Climate Resilience Toolkit*. Retrieved January 20, 2020, from https://toolkit.climate.gov/content/glossary

Virginia Tech. (2011). *Hazard Assessments*. Retrieved February 9, 2021, from https://www.ehss.vt.edu/programs/haz_assess_intro.php

Wainschel, M. (2006). Business Continuity Terminology Update. *Continuity Insights, 4*(1), 54-55.

WDOT. (2020). *Design Manual.* Madison, WI: Wisconson Department of Transportation.

Weilant, S., Strong, A., & Miller, B. (2019). *Incorporating resilience into transportation planning and assessment.* RAND Corporation.

Wikipedia. (2021, January 13). *Risk aversion*. Retrieved from https://en.wikipedia.org/wiki/Risk_aversion

Yale University. (1998). *Probability Models*. Retrieved February 9, 2021, from http://www.stat.yale.edu/Courses/1997-98/101/probint.htm

Zeitman, J., & Ramani, T. (2011). *Sustainability Performance Measures for State DOTs and Other Transportation Agencies. NCHRP Project 08-74.* Washington, D.C.: National Academies Press.

Zieglmeier, V. (2016). Resilience Metrics. *Network Architectures and Services, 9*, 1-15. doi:10.2313/NET-2016-09-1_02

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APPENDIX B – LITERATURE REVIEW

NCHRP Project 23-09

Scoping Study to Develop the Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis

Task 1B Deliverable - Research and Existing Activities Review

Prepared by

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February 17, 2021

National Cooperative Highway Research Program

Transportation Research Board
National Research Council

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1 Introduction

This project's primary objectives are to (1) develop a comprehensive and consistent set of risk and resilience related terminology and (2) formulate a research roadmap to establish a framework that supports quantitative assessments of all-hazard risk and resilience for State and local departments of transportation (DOTs). These objectives will be met through the conduct of four tasks, the first of which includes three activities –develop a risk and resilience glossary of terms, prepare a state of practice review, and conduct a gap assessment. This report is the second of the three Task 1 activities.

This document summarizes established practices, innovative approaches, and research efforts related to the risk and resilience analysis of highway assets. Section 1.1 of this report summarizes the process applied to identify relevant literature, while Section 1.2 provides a summary of findings. Section 2 through 8 of this report delve into specific aspects of risk and resiliency, including:

- Section 2 - Policies
- Section 3 - Definitions
- Section 4 - Assessment Methodologies and Metrics
- Section 5 - Detailed Assessment Methodology Components
- Section 6 - Assessment Tools
- Section 7 - Performance Tracking
- Section 8 - Implementation Challenges

The document is based on a thorough, comprehensive literature review related to risk and resilience analysis approaches of highway assets, including policies in transportation, performance indicators, guidance and frameworks, and tools.

1.1 Identifying Documents for Review

To identify documents for review, the research team first compiled a working list of 230 active and past research reports where risk and resilience were discussed or utilized in highway asset analysis. This list is in Appendix A and includes general research reports, state asset management plans, guidelines, state performance reports, management tool application documents, and state policies and recommendations. While transportation is the central focus of this project, literature from other relevant fields was included for added insight. The search included:

- Traditional academic journal databases via Google Scholar

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- TRB's integrated database, TRID
- AASHTO's TAM Portal
- Review of U.S DOT website, as well as state DOT websites, and publications
- Materials suggested by resiliency and risk management experts at each firm.

The research team briefly reviewed the list of 230 documents, with summary comments on the document relevance included in a table of resources. The resource review was organized by section in a shared excel document to add input for the whole research team. This allowed easy access and comprehension of each topic covered in the following literature review. Each resource had a link to access the complete publication, the type and date of publication, comments relating to the document, and the name of the contributing research team member that provided it. The format of this review allowed the team to pull the necessary resources easily and efficiently when producing the review itself. The entire table is available to the NCHRP 23-09 Panel through a Shared Drive. From this list of 230 documents, 219 documents were deemed relevant and helpful. These form the basis of the literature review in the remainder of this report.

1.2 Key Findings in the Literature

The research team made the following key observations about the findings in the literature review:

- In many cases, risk and resilience concepts are used interchangeably among State and local DOTs. There is a need for education to help transportation professionals understand how these two terms relate and the relevant metrics for each term.
- It has been observed that many metrics for resilience incorporate the use of risk measures. There is an inverse relationship between risk and resilience where reducing risk increases resilience and vice versa. However, other factors such as planning for a response, recovery, and adaptation play a significant role in system resilience.
- There are minimal differences in AASHTO and FHWA definitions for risk and resilience. Many states have adopted either the FHWA or AASHTO risk and resilience definitions. However, some states have developed their definitions.
- Most states are currently performing risk assessments by using simple risk registers based on a five-point rating that relies on a collective judgment. A few state DOTs are expanding their initiatives and incorporating quantitative methodologies for risk and resilience assessments.

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- Multiple federal transportation agencies, state DOTs, and Metropolitan Planning Organizations (MPOs) have performed vulnerability assessments using the FHWA Vulnerability Assessment and Adaptation Framework (VAAF) or a variation of it during FHWA sponsored resilience pilot projects.
- There is no standard methodology for performing quantitative risk and resilience assessments for transportation agencies; however, other sectors such as the wastewater industry and the energy industry have developed methods that are more widely adopted and applied in their industries.

The research team for NCHRP 23-09 will further expand on key findings and more specifically, gaps in the state of practice in the subsequent report to this one as a part of Task 1.3 - Gap Assessment of State of Practice Review. The gap assessment will help support the development of topics for discussion in the industry meetings in Task 2 and help inform the development of the research roadmap and research needs statements in Task 3 of this NCHRP study.

2 Risk and Resilience Policies in Transportation

Risk and resilience policies within transportation agencies have been mostly informal for decades but are currently being formalized and expanded upon in many areas, including being integrated into the core agency operating strategy. The process began with the implementation of the Moving Ahead for Progress in the 21st Century Act (MAP-21) (The Moving Ahead for Progress in the 21st Century Act (MAP-21)), enacted in 2012, followed by the Fixing America's Surface Transportation Act (FAST Act) (Fixing America's Surface Transportation Act (FAST Act), 2015), enacted in 2015. These laws effectively required DOTs to enact risk management policies, localizing them in each DOT's Transportation Asset Management Plan (TAMP).

MAP-21 introduced the concept of a TAMP, enforcing the importance of integrated and optimized asset, performance, and risk management. Reforms to the transportation planning process included "incorporating performance goals, measures, and targets into the process of identifying needed transportation improvements and project selection (The Moving Ahead for Progress in the 21st Century Act (MAP-21))." The FAST Act expanded on MAP-21, providing long-term funding for surface transportation infrastructure planning and investment. FHWA regulations following the FAST Act introduced performance measures and thresholds, with the performance measures based on three categories, summarized in Table 1.

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Table 1. FHWA Required Performance Measures

Measures	Metrics for Performance Measures
PM1 Safety	Number and rate of fatalities per 100 million vehicle-miles traveled
	Number and rate of serious injuries per 100 million VMT
	Number of non-motorized fatalities serious injuries
PM2 Infrastructure Condition	Percentage of pavement in good and poor condition (Interstate and NHS)
	Percentage of bridge deck area in good and poor condition (Interstate and NHS)
PM3 System Reliability	Percentage of reliable person-miles traveled (Interstate and NHS)
	Truck Travel Time Reliability Index (TTTR)
	Total emissions reduction for applicable criteria pollutants

It was expected that DOTs would perform risk management through their TAMPs by identifying risks, prioritizing them, and presenting mitigation strategies. Many states created "risk registers" to accomplish the first two steps. For example, the California Department of Transportation (Caltrans), one such agency that created a risk management handbook that outlines guidelines and considerations for a risk register, recommends a risk register for any Caltrans project but requires it if the project cost is over $1 million. The guidebook includes three levels of risk register detail that may apply to a project contingent on several variables, primarily project cost (Caltrans, 2018). Additional that are considered in determining what level of risk analysis and management should be included are:

- Political Sensitivity
- Type of project
- Location of the project and the community it serves
- Duration of the project
- Project stakeholders
- Project Sponsor's sensitivity to changes in project schedule/cost
- Level of scoping and/or preliminary planning has been done previously

In 2017, CFR Title 23 Part 515 (CFR 2017 Title 23 Part 515), deemed the asset management rule, was put in place, stating that state departments shall "develop a risk-based asset management plan that describes how the National Highway System (NHS) will be managed…." This included establishing a process for conducting performance

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gap analysis, life-cycle planning, development of a risk management plan, development of a financial plan, and development of investment strategies at minimum.

According to the Code of Regulations Title 23, Part 450.306(b)(9), the metropolitan transportation planning process should address the improvement of "resiliency and reliability of the transportation system…" (Code of Federal Regulation). As a result of this policy, DOTs should consider resilience as a planning factor when assessing projects, strategies, and services.

In addition to the federal requirement of developing risk-based asset management plans, MAP-21 requires State DOTs to conduct periodic evaluations of roads and bridges that have needed repairs or reconstruction on two or more occasions due to catastrophic events and decide whether there are suitable alternatives. This requirement was established to conserve Federal resources and promote public safety. Specific deadlines for implementing this policy were published in 23 CFR Section 667. States had to do the first review by November 23, 2018, and then update the reviews every four years as needed. Follow-on reviews had to be completed by November 23, 2020. These reviews must be summarized in TAMPS and integrated into transportation plans and programs (The National Academies of Sciences, Engineering, and Medicine, 2020). As per 23 CFR Section 551, the periodic reviews described in 23 CFR Section 667 require TAMPs to incorporate the following guidance. Specifically, by April 2018, TAMPS should:

- Establish a planning process for the entire life cycle of assets that considers current and future conditions, i.e., climate change, extreme weather events, seismic events, etc. (23 C.F.R. 515.7(b)).
- Establish a risk-based asset management plan that includes risk assessments that address current and future conditions, address reoccurring damage and the associated costs, estimate the likelihood of risks, prioritize risks, and develop a mitigation plan for the highest priority risks (23 C.F.R. 515.7(b)).

Between the 51 states' TAMPs, there are many methods to implement risk and resilience strategies.

The formal discussion around emerging standard policies being utilized has established a starting point for DOTs to begin by setting the standard for what is expected. From there, informal norms have been developed and serve as the main source of guidance to improve and enhance asset management practices. Many states have built on the policies, tailoring definitions and requirements to serve their needs best, enhancing the field.

Different efforts have been made to help agencies implement Risk and Resilience analysis in transportation activities.

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2.1 Federal Transportation Risk and Resilience Initiatives

Federal, state, and local governments invest in their transportation infrastructure daily. Transportation is a long-term investment with many inherent risks to that daily investment including natural disasters, operational and funding gaps, asset condition and performance and more. The industry also lacks standard methods in assessing risk and determining the appropriate distinction between the commonly recognized "negative" risks instead of the justified and even necessary risks involved in optimizing the systematic efficiency.

A current example of this dilemma is considering connected and/or autonomous vehicle technologies on the federal highway system. The current state of the industry indicates enhanced traffic control infrastructure would improve the safety and operational performance of these technologies, an added investment which only benefits, in relation to other vehicles on the road, technologies that are largely yet unproven. However, the risk in not accommodating those emerging technologies can have significant impacts on the local economy, operations, asset condition, etc. Considering the potential impacts has led FHWA to include the State Transportation Innovation Council concept for each state to implement as part of its Every Day Counts Initiative (Federal Highway Administration, 2020).

Natural risks also encourage strategic initiatives for risk mitigation. From record setting hurricanes along the south and east coasts, wildfires ravaging throughout California, flooding in Colorado, and ice storms in Atlanta, assets are being disrupted everywhere (FHWA, Integrating Resilience into the Transportation Planning Process, n.d.). Transportation agencies need to ensure their infrastructure is resilient and prepared for any potential risks to address these issues. Being more resilient is at the top of the list for many initiatives in the coming years. This critical issue was included in the US DOT Strategic Plan for Fiscal Year 2018-2022, where the development of new tools to improve durability and resilience will be a priority. Doing this will extend the life span of essential infrastructure across the United States, but it will also reduce future costs.

In addition to strategic planning, the FHWA put together a white paper project providing a baseline of efforts DOTs and MPOs have already implemented to integrate resilience, as well as a handbook to guide practitioners at all resilience planning levels on how to better integrate resilience into their agencies (FHWA, Integrating Resilience into the Transportation Planning Process-White Paper on Literature Review Findings, n.d.). Many states have cited their incorporation of resilience measures as due to federal regulations, as seen below in Table 2 (FHWA, Integrating Resilience into the Transportation Planning Process, n.d.), or local state policies.

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Table 2. Federal Laws and Regulations That Require Resilience Considerations

Effective Date	Overview	Source
June 27, 2016	"(a) Each State shall carry out a continuing, cooperative, and comprehensive statewide transportation planning process that provides for consideration and implementation of projects, strategies, and services that will address the following factors: (9) improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation."	23 CFR 450.206(a)
June 27, 2016	"(b) The metropolitan transportation planning process shall be continuous, cooperative, and comprehensive, and provide for consideration and implementation of projects, strategies, and services that will address the following factors: (9) Improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation;"	23 CFR 450.306(b)
Long-range statewide transportation plan adopted after May 2018 meets requirements	"(c) The long-range statewide transportation plan shall reference, summarize, or contain any applicable short-range planning studies; strategic planning and/or policy studies; transportation needs studies; management systems report; emergency relief and disaster preparedness plans;"	23 CFR 216 (c)
On or after May 27, 2018, an MPO meets requirements to adopt a metropolitan transportation plan	"(f) The metropolitan transportation plan shall, at a minimum, include: 7) Assessment of capital investment and other strategies to preserve the existing and projected future metropolitan transportation infrastructure, provide for multimodal capacity increases based on regional priorities and needs, and reduce the vulnerability	23 CFR 450.324(f)(7)

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	of the existing transportation infrastructure to natural disasters.	
October 2, 2017	Asset Management Plan (c) A State DOT shall establish a process for developing a risk management plan. This process shall, at a minimum, produce the following information: (6) Risk management analysis, including the results for NHS pavements and bridges, of the periodic evaluations under part 667 of this title of facilities repeated damaged by emergency event. and (h) A State DOT shall integrate its asset management plan into its transportation planning processes that lead to the STIP, to support its efforts to achieve the goals in paragraphs (f)(1) through (4) of this section.	23 CFR 515.7 (c)(6) and 515.9 (h)
Mandatory and due by November 23, 2018	State DOTs must evaluate facilities that have repeatedly been damaged in emergency events.	FAST Act 23 CFR 667
Nonbinding	The National Highway Freight Program has a goal to "improve the . . . resiliency of freight transportation in rural and urban areas."	FAST Act
Nonbinding	Goals for the national transportation system include increasing safety, security, and reliability.	MAP-21
Nonbinding	National Infrastructure Protection Plan invests to produce significant reductions in national risk.	Department of Homeland Security

Another effort by the Federal government to assist in the incorporation of resilience measures is the ability for states to use Emergency Relief (ER) Program funds on improving long-term resilience on Federal-aid highways, as long as it is consistent with current standards and economically justified (FHWA, Kalla, & Shepherd, Integration of Resilient Infrastructure in the Emergency Relief Program, n.d.). This allows states to bounce back from disasters and create stronger, more resilient assets for any future impacts.

We are still learning the full extent of how the impacts of natural disasters and climate change that are constantly threatening critical infrastructure affect transportation systems. There are many proactive measures being taken by states, but there is still an opportunity to learn more and integrate even more resilient efforts. A study shows four

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pathways of disruption to transportation systems as a result of climate change and extreme weather events, as seen in Figure 1 (Markolf, Hoehne, Fraser, Chester, & Underwood). Infrastructure systems are only becoming more complex and interconnected, along with the constantly evolving challenges and threats. The movement toward gaining a better understanding and implementing effective measures is crucial to creating a more resilient infrastructure.

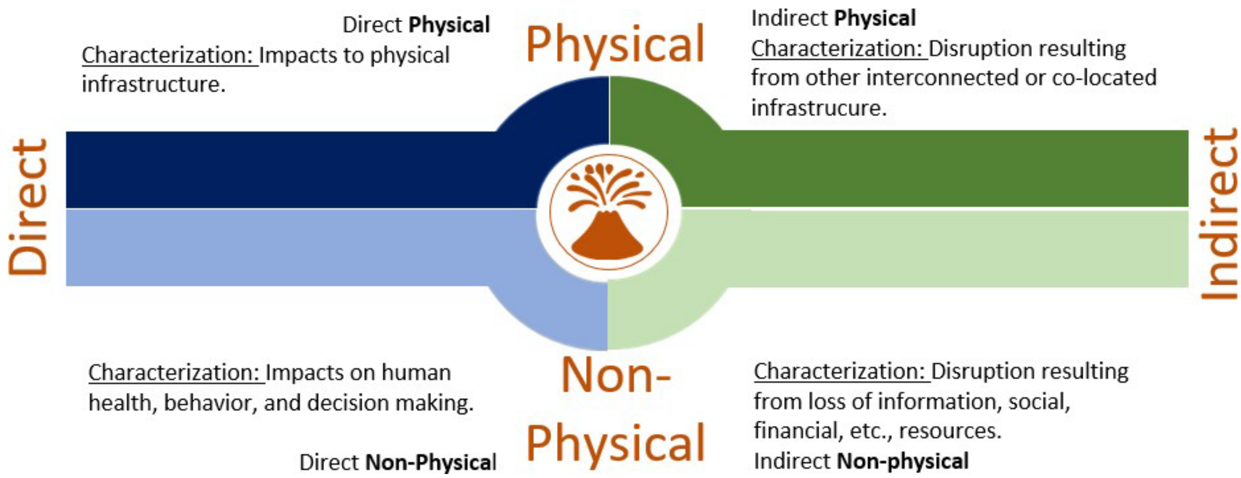

Figure 1. Four Pathways of Disruption to the Transportation System, Adapted from (Markolf, Hoehne, Fraser, Chester, & Underwood)

The United States Government Accountability Office took a closer look at the impact of climate change on coastal communities and areas impacted by environmental risks (USGAO, 2020). The plea was made in Congress to consider establishing a federal pilot program solely dedicated to climate migration. Climate migration is the action of retreat or relocation from vulnerable areas to combat the effects of climate change on many communities. Current federal programs provide limited support, and assistance has been very slow for areas in need. Implementing a program focused on supporting impacted communities will ultimately enhance the nation's climate resilience and reduce federal fiscal exposure.

Risk and resilience in US transportation agencies have been occurring informally for decades. A formalized practice began with MAP-21 in 2012 (The Moving Ahead for Progress in the 21st Century Act (MAP-21)) and the FAST Act in 2015 (Fixing America's Surface Transportation Act (FAST Act), 2015), as well as many other regulations that can be seen in Table 2. These initial federal authorization bills guided the development of state TAMPs, a requirement for all DOTs to ensure risk management is being considered. The various TAMPs showcase the various informal norms and standards developed and used over the years while implementing risk and resilience measures.

While standard definitions have evolved from FHWA and AASHTO, many states have certain objectives and practices specific to their state needs and tailor their

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understanding of risk and resilience to better align with their initiatives. The FHWA has a Final Rule for risk management processes, as seen in Figure 2 below that sets the general guidance and approach for the state (Caltrans, 2019).

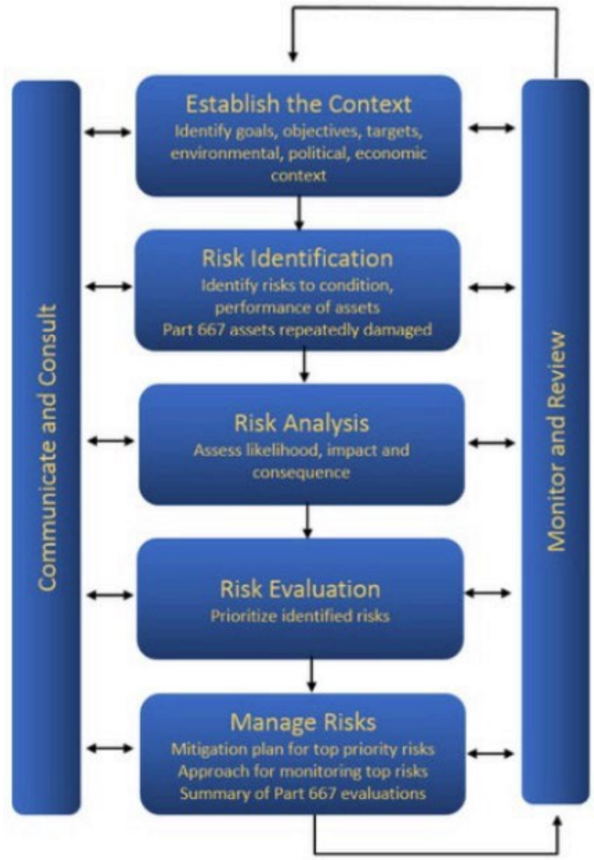

Figure 2. Risk Management Process defined by FHWA Asset Management Final Rule (Caltrans, 2019) .

In 2017, the FHWA developed interim guidance called, "Incorporating Risk Management into Transportation Asset Management Plans". The document "guides the risk element of the TAMP, defines risk, and provides guidance on how the risk element can be applied to meet risk-based TAMP requirements" (FHWA, 2017). The guidance assists agencies in developing their TAMPs, encouraging the use of risk and resilience practices throughout all departments.

Multiple NCHRP reports have dissected the deployment of risk and resilience practices in State DOTs, developing guidance and tools for their incorporation. NCHRP 20-117 created a Transportation Resilience Guide and Toolkit and a national summit and peer exchange on transportation resiliency (Hammond). The creation and implementation of these tools helps states deploy greater risk and resilience initiatives, learning from other transportation agencies and practitioners. NCHRP 08-93, *Managing Risk across the Enterprise: A Guide for State Departments of Transportation*, was published in 2016 and provided a "comprehensive framework to identify and manage risk" for state DOTs

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(Proctor, Varma, & Roorda). The guidance lays out a step-by-step process for practitioners and agencies to add risk management and resilience measures into already incorporated management processes. This concept can be seen in Figure 3 below (Proctor, Varma, & Roorda).

Figure 3. Illustration that Risk Management and Performance Management Operate as Parallel (Proctor, Varma, & Roorda)

Another report, "Incorporating Resilience into Transportation Planning and Assessment," was initiated and explored incorporating resilience into long-term transportation planning efforts by State DOTs and MPOs (Weilant, Strong, & Miller, Incorporating Resilience into Transportation Planning and Assessment, 2019). A framework was developed, using interviews with stakeholders at DOTs and planners in MPOs and reviews of published literature to create a logic model for incorporating resilience methods. It was developed in the interest of DOT and MPO planners, with the intent to be used to "modify long-term transportation planning processes to better incorporate resilience."

While there is no specific national guidance, there are many resources available to guide transportation agencies in various directions, depending on their wants and needs. The development of new methods and practices is constantly evolving, and the implementation of risk management and resilience measures is more important now than ever.

2.2 International Requirements for Risk-Based Asset Management

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Maximizing return while also being environmentally responsible and safe is more critical than ever before. Aligning these together can be tricky, and misalignment may cause time, funds, and resource waste. To combat this, the International Organization for Standardization (ISO) 55000 was created in 2014. This standard took the place of PAS 55 Asset Management, a similar standard with a key difference that PAS 55 focused on physical assets only (ISO 55001 Asset Management supersedes PAS 55, n.d.). ISO 55000 is a family of standards providing three sets of information to assist risk-based asset management (Sanford, 2015).

- ISO 55000 - Asset Management - Overview, principles, and terminology
- ISO 55001 – Asset Management – Management systems – Resources
- ISO 55002 – Asset Management – Management systems – Guidelines for the application of ISO 55001

These three standards are essential because they "represent a global consensus on what asset management is and what it can do to increase the value generated by all organizations (Sanford, 2015)." The standards clarify organizational context, define leadership and support roles, specify performance evaluation elements and other key components to successfully manage risk.

3 Risk and Resilience Definitions

Risk and Resilience terms have been used interchangeably and applied in different sectors and fields of study; however, they have different definitions and measures. This section presents an overview of some of the definitions and metrics used in the transportation sector for each term.

3.1 Risk Definitions

Many definitions of risk exist in many sectors. Most colloquial definitions of risk share the same elements, including uncertainty or probability, an unpleasant event, and injury or damage.

The International Organization for Standardization's (ISO) 31000 guide to risk management (International Organization for Standardization (ISO), 2018) states that "Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence." The ISO's guide to risk assessment for structures adds the additional dimension of severity: "Risk is a 'combination of the probability or frequency of occurrence of an event and the

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magnitude of its consequence." (International Organization for Standardization (ISO), 2018)

Another definition of risk is presented by The American Society of Mechanical Engineers (ASME) guidebook to the Risk Analysis and Management for Critical Asset Protection (RAMCAP Plus SM) (ASME, 2009) method for risk assessment. RAMCAP defines risk as "the potential for loss or harm due to an untoward event and its adverse consequences.

In the transportation sector, The American Association of State Highway and Transportation Officials (AASHTO) states in its *Guide for Enterprise Risk Management* that risk "involves more than just threats or hazards" and defines risk as "the positive or negative effects of uncertainty or variability on agency objectives" (AASHTO, Guide for Enterprise Risk Management: Quick Guide, 2016)

The FHWA asset management rulemaking (23 CFR 515.5) provides the same definition for risk as the *AASHTO's Guide for Enterprise Risk Management*. Transportation agencies frequently adopt this definition, and it has been included in multiple state DOTs Transportation Asset Management Plans (TAMPS), including Colorado DOT (CDOT, 2019), Kansas DOT (KDOT, 2019), and Minnesota DOT (MnDOT, 2019), among others. In addition, many transportation agencies have adopted FHWA's risk definition stated on 23 CFR 515.5 or developed their definition. Table 3 presents some standard risk definitions. Many definitions of risk share notions of probability and adverse effects and how risk is calculated by multiplying uncertainty times a measure of consequences.

Table 3. Examples of Risk definitions

Definition	Source
An uncertainty that can have either positive or negative impacts	Colorado Department of Transportation, Risk and Resilience Analysis Procedure, 2020
A combination of the likelihood that an asset will experience a climate impact and the severity or consequence of that impact.	FHWA Vulnerability Assessment and Adaptation Framework, 3rd Edition, 2018
The potential for loss or harm due to an untoward event and its adverse consequences.	All-Hazards Risk and Resilience: Prioritizing Critical Infrastructure Using the RAMCAP Plus Approach, ASME Press, 2009
effect of uncertainty on objectives	ISO 31000, 2009
the positive or negative effects of uncertainty or variability on agency objectives	AASHTO Guide for Enterprise Risk Management: Quick Guide, 2016
A combination of the magnitude of potential consequence(s) of climate	Adapting to the Impacts of Climate Change, America's Climate Choices: Panel on Adapting to

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Definition	Source
change impacts(s) and the likelihood that the consequence(s) will occur.	the Impacts of Climate Change, National Research Council, (2010).
"Measure of the probability and severity of an adverse effect to life, health, property, or the environment." "Probability of an adverse event times the consequences if the event occurs."	SSMGE TC32 - Technical Committee on Risk Assessment and Management Glossary of Risk Assessment Terms – Version 1, July 2004

3.2 Resilience Definitions

Similar to the definition for risk, there is also no universal definition of resilience or resiliency. Many definitions have evolved in different sectors and fields of study (see Table 4). However, there are many parallel definitions found within the literature. Some highly cited definitions for resilience outside the transportation sector includes a definition from the U.S. Department of Homeland Security (USDHS) who defines resilience on the 2009 edition of the National Infrastructure Protection Plan (NIPP) (DHS, 2009) as "The ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions." The Rand Corporation Report (2019) (Weilant, Strong, & Miller, Incorporating resilience into Transportation Planning and Assessment, 2019) expands upon these themes:

- "Reducing the likelihood of a disaster and increasing the ability of a community to absorb or resist a shock."
- "Increasing the adaptability of a system while maintaining functions in the presence of a shock."
- "Reducing the time to recovery to normal functioning, which might be different from pre-event functioning."

Similarly, the National Academy of Science (NAS) defines resilience as "the ability to plan and prepare for, absorb, recover from, and adapt to an adverse event." (Council, 2012) A compiled collection of similar definitions from researchers within the transportation sector include (Freckleton, Heaslip, Louisell, & Collura, 2012):

- "A system's ability to maintain its demonstrated level of service or restore itself to that level of service in a specified time frame" (Serulle, Heaslip, & Brady, 2011).
- "A characteristic that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed" (Battelle, 2007).

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- "A system's ability to accommodate variable and unexpected conditions without catastrophic failure" (Litman, 2007).
- "A system's ability to absorb the consequences of disruptions to reduce the impact of disruptions and maintain freight mobility" (Ta, Goodchild, & Pitera, 2009).

Definitions of resilience from outside the transportation sector emphasize the ability to withstand or recover from a disruption.

In 2009, the AASHTO-TRB Transportation and Security Summit proposed the following definition: "The ability of a system to provide and maintain an acceptable level of service or functionality in the face of major shocks or disruptions to normal operations" (AASHTO, 2016), (Flannery, Pena, & Manns, Resilience in Transportation Planning, Engineering, Management, Policy, and Administration, 2018). However, the most recent definition from AASHTO's Special Committee on Transportation Security and Emergency Management (SCOSTEM) states that resilience is "the ability to prepare for, absorb, recover from, or more successfully adapt to adverse events" (AASHTO, 2016). Further, FHWA Order 5520 defines resilience as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions."

Many transportation agencies have adopted FHWA's definition or developed similar definitions for their purposes, as illustrated in Table 4. An FHWA white paper pointed out that most State DOT and MOPs resilience definitions focus on "the ability to prepare for and recover from disasters and disruptive events" but vary on "how agencies propose to build that ability with some emphasizing adaptive capacity and robustness, while other prioritize swiftness in recovery response (Dix, Zgoda, Vargo, Heitsch, & Gestwick, 2018)." As part of this project, a Glossary of Terms was developed with a more extensive list of risk and resilience related terminology.

Table 4. Examples of Resilience Definitions Used by Transportation Agencies

Transportation Agency	Resilience Definition
Anchorage Metropolitan Area Transportation Solutions	"resilience means how to work around outcomes to get back up running quickly. "
Arkansas DOT	"resilience also implies transformation, so not only is the infrastructure serviceable to survive or recover but it can adapt to a changing environment in which it operates."
Baltimore Regional Transportation Board	states that resilience means its system is "better able to adapt to a variety of potentially significant future changes."

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Colorado DOT	"Resilience is the ability to keep our roads open and functional in the face of unexpected events and challenges." "The ability of a system to rebound, positively adapt to, or thrive amidst changing conditions or challenges, including human-caused and natural disasters, and to maintain quality of life, healthy growth, durable systems, economic vitality, and conservation of resources for present and future generations."
Minnesota DOT	"reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs."
Northeast Ohio Areawide Coordinating Agency (NOACA)	"Resiliency is a process for managing complex infrastructures rather than a single outcome… As such, a resiliency framework takes an adaptive life-cycle approach to tackling the dynamic challenges that confront today's complex infrastructure systems. Embedded in it is the capability to protect its assets, anticipate and detect threats, prevent risks of known failures, withstand unanticipated disruptions, and respond and recover rapidly when the worst does happen."
Rockingham Planning Commission	"a capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment."
San Francisco Metropolitan Transportation Commission (MTC)	"includes a desire to "enhance climate protection and adaptation efforts" in its definition of resilience."
Tennessee	"The ability of the transportation system to withstand and recover from incidents."
Wisconsin DOT	"a resilient transportation system is able to quickly respond to unexpected conditions and return to its usual operational state."

3.3 Relationship Between Risk and Resilience

As mentioned previously, risk and resilience terms are often used interchangeably due to misconception. To better understand the relationship between risk and resilience, a review of some common definitions is in order. Risk can be described as an event that may cause either harm or improve a situation (opportunity) and is associated with some probability of occurrence. Risk management, on the other hand, is an action taken to mitigate risk. Typical risk management strategies include: 1) avoid, 2) reduce, 3)

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tolerate, 4) transfer and 5) take advantage of (i.e., "don't let a good crisis go to waste."). Several example definitions of resilience include the following:

- **FHWA** — "to anticipate…and adapt to changing conditions, and withstand, …and recover rapidly from disruptions."
- **National Research Council** — "…absorb, recover from, or more successfully adapt to adverse events".
- **From Ecology** (Hodgson, McDonald, & Hosken, 2015) – "…the ability of a system of a system to resist and recover from a disturbance."

Common themes found in definitions of resilience include resisting and recovering from a disruption. There is an inverse relationship between risk and resilience. Natural and manmade threats can negatively affect a system's resilience. A threat or hazard can disrupt a system and impede recovery. The risk associated with a threat can be measured using the probability of an adverse event with an unknown severity causing an unknown degree of damage, disruption, or service loss. On the other hand, an agency can take the opportunity to reduce the likelihood of an adverse event or mitigate its impacts, thus increasing system resilience. As Flannery et al. (2018) (Flannery, Pena, & Manns, Resilience in Transportation Planning, Engineering, Management, Policy, and Administration, 2018) states, "when risk or the expected financial loss decreases, resilience increases. By reducing vulnerability to a threat (moving toward a value of 0), resilience is highest, and the expected risk tends toward zero." This relationship between risk, resilience, and vulnerability is visualized in a graphic prepared by the Department of Homeland Security (see Figure 4) (DHS, 2010). In the graph, risk and resilience are inversely related. As vulnerability increases, so does risk. Resilience, in this case, is measured in terms of the time it takes a system to return to normal functioning, i.e., performance-time units. As vulnerability increases, resilience decreases and the time it takes to restore a system to full functioning is longer.

Even though risk and resilience have different meanings, they are interrelated. However, reducing risk and vulnerabilities is not the only way to increase resilience in a system. The anticipated planning on how to respond, recover and adapt to possible disruptions also plays a vital role in improving the resilience of a system.

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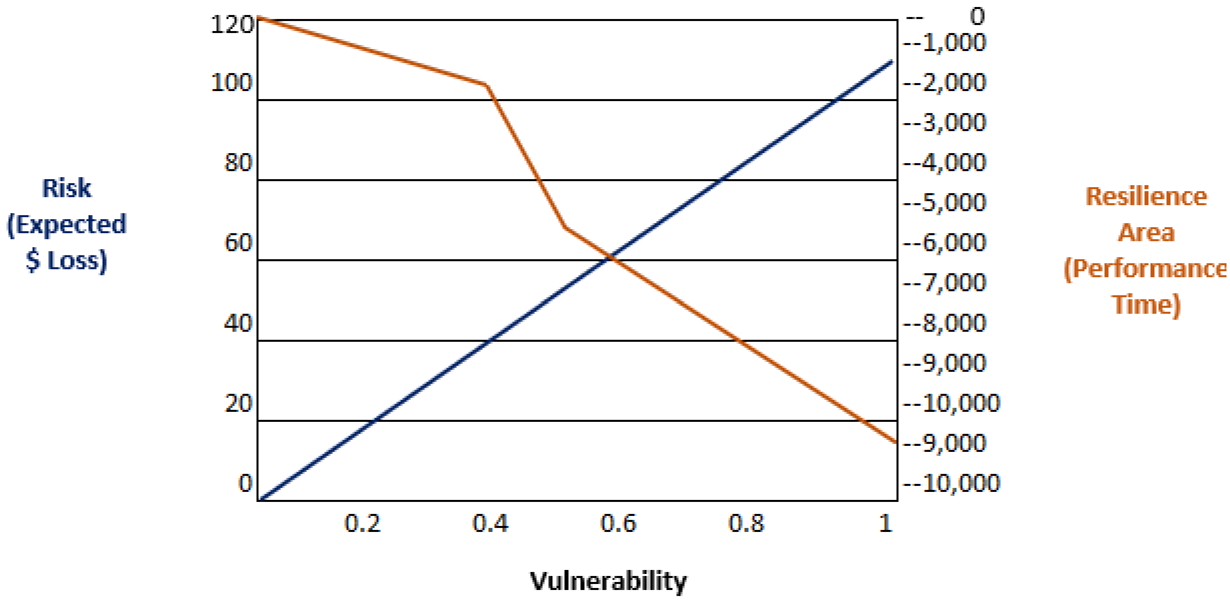

Figure 4. Relationship between Risk, Resilience, and Vulnerability, adapted from (DHS, 2010)

As stated in the findings from *Understanding Transportation Resilience: a 2016-2018 Roadmap report* (AASHTO, 2016), Resilience from the DOT perspective has three different viewpoints: planning, engineering, and operations over two different periods: pre-event (risk reductions and post-event (consequence reduction).

3.4 Frameworks for Risk and Resilience

Addressing the challenge of integrating resilience into all facets of a transportation agency's activities requires a framework. Risk and resilience frameworks provide a conceptual structure, logic, and potentially even various tools to frame and estimate risk and resilience. Different risk and resilience frameworks have been developed and applied in the transportation sector.

One of the most common frameworks developed for risk management is the International Organization of Standardization ISO 31000:2009 (International Organization for Standardization (ISO), 2018). This framework can be applied to any field and is based on steps that should help identify risks and develop a communications structure with stakeholders (see Figure 5).

Another framework developed by the American Society of Mechanical Engineers (ASME) has been implemented in different sectors, including transportation. ASME forged a management process to estimate risk and resilience to various assets from multiple hazards. This process is called Risk Analysis and Management for Critical Asset Protection (RAMCAP Plus) (ASME, 2009). RAMCAP includes a 7-step framework process that helps estimate and manage risk and resilience as part of this effort. Figure 6

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shows the RAMCAP Plus framework. Figure 5 summarizes some common industry frameworks and risk and Resilience assessment/management standards

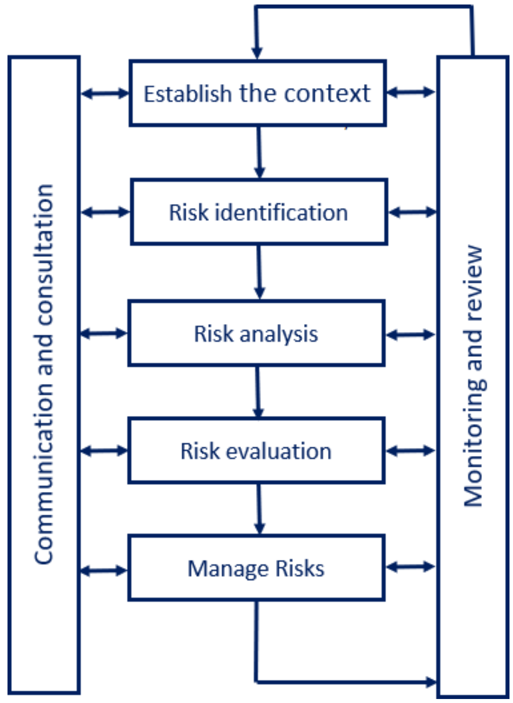

Figure 5. ISO's 3100:2009 Risk Framework, adapted from (International Organization for Standardization (ISO), 2018)

Figure 6. The Seven Steps of the RAMCAP™ Plus Process

Table 5 summarize several risk assessment frameworks from around the world.

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Table 5. Example of Industry Risk and Resilience Frameworks/Standards

CSA 1997	BS 6079-3 (2000)	IRGC 2004	COSO (2004)	AS/NZ4360 (2004)	ISO 31000 (2009)	ASME - RAMCAP Plus^{SM} (2009)
1. initiation 2. preliminary analysis 3. estimation 4. evaluation 5. control 6. action or monitor 7. communicate	1. context 2. identification 3. analysis 4. evaluation 5. treatment 6. communicate 7. review and update	1. pre-assessment 2. appraisal 3. tolerability judgment 4. risk management 5. communicate	1. environment 2. objectives 3. identification 4. assessment 5. response 6. control 7. communicate 8. monitoring	1. context 2. identification 3. analysis 4. evaluation 5. treatment 6. communicate 7. monitor and review	1. mandate 2. context 3. identification 4. analysis 5. evaluation 6. treatment 7. communicate 8. consult 9. monitor and review	1. asset characteriz-ation 2. threat characteriz-ation 3. consequence analysis 4. vulnerability analysis 5. threat assessment 6. risk and resilience assessment 7. risk and resilience management

Key: CSA – Canadian Standards Association; BS – British Standard; IRGC – International Risk Governance Council; COSO – Committee of Sponsoring Organizations; AS/AN – Standards Australia and Standards New Zealand; ISO – International Standards Organization; ASME – American Society of Mechanical Engineers

There are no standard frameworks to estimate risk and resilience in the transportation sector. However, many efforts from FHWA and AASHTO have focused on developing frameworks for risk management. To help transportation agencies to incorporate risk management in their Transportation Management Plans (TAMPs), the AASHTO Transportation Management Guide- A Focus in Implementation illustrates a typical risk management framework (see Figure 7) that can be used for multiple activities in an organization from specific projects to corporate management (AASHTO, AASHTO Transportation Asset Management Guide—Executive Summary, 2013).

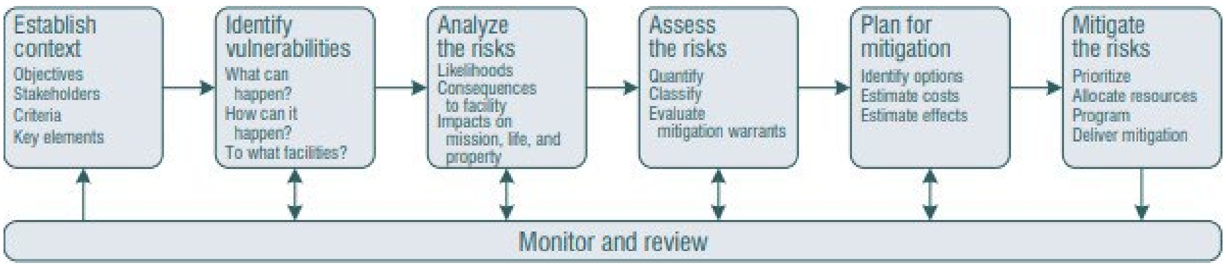

Figure 7. Typical Risk Management Framework (AASHTO, AASHTO Transportation Asset Management Guide—Executive Summary, 2013)

In addition, The U.S. DOT's Volpe National Transportation Systems Center drafted a resilience framework in 2013 (Volpe, 2013). Volpe's framework is based on defense in depth, life-cycle cost analysis, and adaptative measures.

Figure 9 presents a diagram of the Volpe resilience framework.

Many other frameworks have been developed in the public and private sectors applicable to risk management. NCHRP 08-93 provides an overview of some of these frameworks in their final literature review report (Proctor, Varma, & Roorda).

A common theme in most of these frameworks is the identification of vulnerabilities, consequences, and threats that may cause disruptions to the transportation network or system, along with the title of possible mitigation strategies to reduce the risk

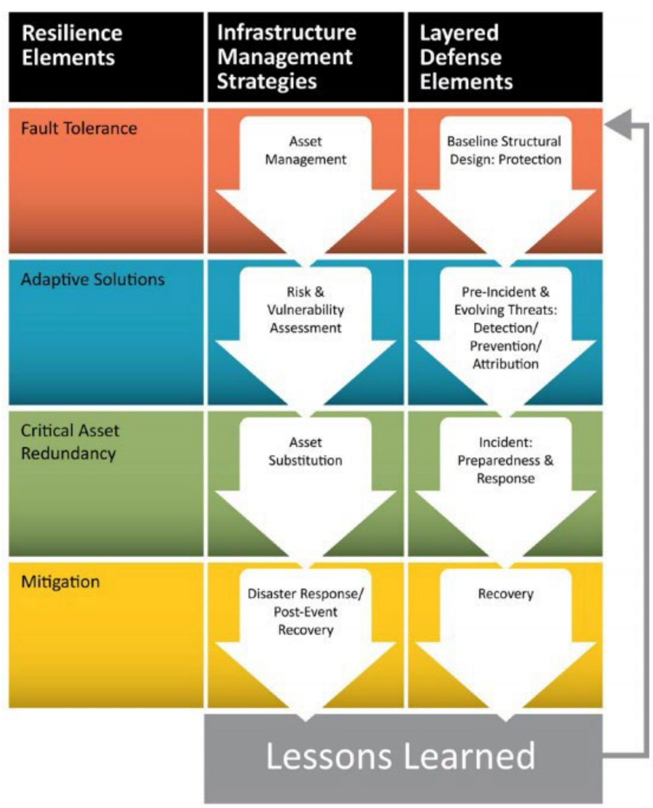

Figure 8. Volpe Infrastructure Resilience Framework (Volpe, 2013)

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and increase resilience. These frameworks or processes provide a tool to stakeholders to help them plan and prioritize investments.

In summary, a framework is a system for solving complex problems. Some proposed resilience frameworks emphasize adaptability, recovery, and long-term planning, while others focus on transportation's core mission of providing reliable mobility to all users.

4 Methods of Risk and Resilience Assessment, Metrics and Performance Indicators

As found in literature and practice, there are many definitions for risk and resilience and no standard methodologies or metrics associated with these terms. This section presents an overview of some assessment methodologies and metrics for risk and resilience and performance indicators used in the industry.

4.1 Risk Assessment Methodologies and Metrics

Risk analysis or assessment may be classified into qualitative, quantitative a combination of both. These models may vary by degree of complexity –some using simple methods and others applying more sophisticated probabilistic methods. This next section provides an overview of these methods.

4.1.1 Qualitative Risk Assessment Methods

Qualitative risk models are widely used throughout the public and private sectors because of their ease of use and limited data requirements. They can be applied when analyzing strategic goals and related items. Qualitative risk models produce non-numerical estimates of risk using categorical metrics like "low," "medium," and "high," or a scale of discrete numbers, as illustrated in Figure 9 (FHWA, 2017).

		Values	L X I - Consequence			
Likelihood	Almost Certain	5	5	50	200	350
	Probable	4	4	40	160	280
	Possible	3	3	30	120	210
	Rare	2	2	20	80	140
	Exceptionally Rare	1	1	10	40	70
			1	10	40	70
			Low	Moderate	High	Severe
			Impact			

Figure 9. Example Qualitative Risk Matrix, adapted from (FHWA, 2017)

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In addition, other examples of qualitative approaches include risk matrices and weighted index models where the weighted score is calculated for each variable based on an integer scale, e.g., from 0 (low) to 4 (high). The integer scores reflect the relative significance of a given variable's value and should be based on expert opinion.

Risk matrices are employed across all sectors because of their simplicity. Unlike multi-criterion models that can be implemented with GIS or spreadsheets, risk matrices are usually built with spreadsheet tools, such as Microsoft Excel. A Risk Matrix is a two-dimensional relative risk model. The matrix ranks consequences on the horizontal axis and relative likelihood on the vertical axis. Subject matter opinion is relied upon, in many cases, to determine likelihood and consequences. Figure 10 presents a qualitative risk assessment and metrics (FHWA, 2017). Risk matrices are widely used in the transportation sector. Figure 10 shows an example of a qualitative risk metric used in transportation risk management (Curtis, et al., 2012).

Level	Likelihood
A	Remote
B	Unlikely
C	Likely
D	Highly Likely
E	Near Certainty

ASSESSMENT GUIDE

Likelihood	a	b	c	d	e
E	M	M	H	H	H
D	L	M	M	H	H
C	L	L	M	M	H
B	L	L	L	M	M
A	L	L	L	L	M

Consequence

RISK ASSESSMENT

High (Red)

Unacceptable. Major disruption likely. Different approach required. Priority management attention required

Moderate (Yellow)

Some disruption. Different approach may be required. Additional management attention may be need

Low (Green)

Minimum impact. Minimum oversight needed to ensure risk remains low

Level	Schedule	and/or	Cost
a	Minimal or no impact		Minimal or no impact
b	Additional resources required; able to meet		<5%
c	Minor slip in key milestones; not able to meet need date		5-7%
d	Major slip in key milestone or critical path impacted		7-10%
e	Can't achieve key team or major program milestone		>10%

Figure 10. Heat Map Example for Risk Assessment

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Risk Event	Likelihood	Consequence	Rating
Inadequate information systems **Risk Mitigation Strategy/Treatment:** Invest in updated information systems	0.90	0.70	0.63
Budget Shortfalls **Risk Mitigation Strategy/Treatment:** Monitor budget, prepare contingency program strategies	0.70	0.80	0.56
Inadequate asset inventories **Risk Mitigation Strategy/Treatment:** Invest in updated asset inventories	0.70	0.70	0.49
Maintenance failures **Risk Mitigation Strategy/Treatment:** Increase training, audit maintenance processes	0.70	0.70	0.49
Price increases **Risk Mitigation Strategy/Treatment:** Monitor bid prices monthly and prepare contingencies	0.30	0.70	0.21
Loss of experienced asset management staff **Risk Mitigation Strategy/Treatment:** Institute succession planning, training, mentoring	0.30	0.70	0.21
Changing legislation **Risk Mitigation Strategy/Treatment:** Monitor legislation. Inform legislators of impacts	0.30	0.30	0.09
Economic downturn **Risk Mitigation Strategy/Treatment:** Monitor economic activity and plan contingencies	0.30	0.30	0.09
Public opinion **Risk Mitigation Strategy/Treatment:** Sustain robust public information processes	0.30	0.30	0.09
Environmental standards **Risk Mitigation Strategy/Treatment:** Train staff to comply with standards. Conduct audits.	0.30	0.30	0.09
Lack of management support **Risk Mitigation Strategy/Treatment:** Train mid-level staff. Ensure compliance with TAM.	0.10	0.70	0.07
Barge strikes to bridges **Risk Mitigation Strategy/Treatment:** Install navigational warnings.	0.10	0.70	0.07
Excess vehicular loadings **Risk Mitigation Strategy/Treatment:** Monitor truck weights on vulnerable routes. Urge enforcement.	0.10	0.70	0.07
Rising interest rates **Risk Mitigation Strategy/Treatment:** Monitor interest rates. Time bond issues accordingly.	0.10	0.30	0.03
Flood **Risk Mitigation Strategy/Treatment:** Install storm event gauges. Countermeasures at scour-prone structures.	0.10	0.30	0.03
Seismic events **Risk Mitigation Strategy/Treatment:** Develop contingency planning for detours, emergency repairs.	0.01	0.70	0.01

Figure 11. Sample Risk Register (FHWA, 2012)

An example of risk matrices can be seen in risk registers. Risk registers (see Figure 12) are widely used by transportation agencies to address and document risks. The risk registers include risk characteristics, the cause, affected objectives, likelihoods, impacts, and final risk ratings based on these conditions. In 2012, the FHWA published a series of reports on Risk-Based Transportation Asset Management, and Report 3 described a framework for how risk management principles can be incorporated into TAM plans (FHWA, 2012). Report 3 provided guidance to shift risk management from a project-level practice to a broader strategic-level practice to cover all aspects of asset management. Using risk management in this way can help to mitigate the impacts of crises through proactive action to improve asset maintenance procedures and policies.

As part of a risk management methodology, this report encourages agencies to develop an Asset Risk Register. An Asset Risk Register is a spreadsheet or database that lists an organization's identified risks, ranks them based on likelihood and potential impact, and explains how those risks are being treated or mitigated. This register can make strategic decisions to mitigate the most dangerous risks within an agency's resource limitations and risk tolerance. This methodology is primarily qualitative, focusing on identifying risks and ranking risk severity. NCHRP 08-36, *Development of Risk Register Spreadsheet Tool,* provides a template and instructions for creating a risk register (O'Har, Senesi, & Molenaar, 2016). This tool goes beyond asset-related risks and includes templates for enterprise-level and program-level risk management. Users can use the spreadsheet to manually summarize information about specific risks facing an enterprise or a program within different categories and use the automated features of the tool to populate the risk register and develop a pre-mitigated and post-mitigated heat map of risks, and a risk summary. However, this tool is not a

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substitute for the executive leadership, governance, training, and awareness required for successful Enterprise Risk Management implementation.

4.1.2 Quantitative Risk Assessment Methods

There are a variety of options states choose to move forward with regarding risk their TAMPs, including moving beyond a risk register. Many states are choosing to move beyond risk registers to develop more measurement-based ways to assess risk with their transportation agency. Some of those different processes include Quantitative Risk Assessments (QRA). A formalized and systematic risk analysis approach, a QRA is an essential strategy to understand risk exposure. It also provides insight to make cost-effective decisions and manage lifecycle risks (Engineering Safety Consultants, n.d.). The QRA process reflects a quantitative representation of risk numerically using models that may be simple or complex and deterministic or probabilistic.

Deterministic risk models are based on single values or points and inputs to the equations or model; therefore, these models also generate a single output. An example of the application of this type of model has been incorporated into the American Society of Mechanical Engineers (ASME) methodology for Risk Analysis and Management for Critical Asset Protection (RAMCAP Plus SM) (ASME, 2009). The RAMCAP methodology is an all-hazards risk and resilience management process for critical infrastructure. The formula below, Equation 1, expresses how risk is calculated based on the parameters mentioned

$$Risk = (Threat)\ x\ (Vulnerability)\ x\ (Consequences)$$

Equation 1. Risk Calculation

Where:

- "**Risk** -The potential for loss or harm due to the likelihood of an unwanted event and its adverse consequences. When the probability and consequences are expressed as numerical point estimates, the expected risk is computed as the product of those values."
- **"Threat (T)** - The likelihood that an adverse event will occur within a specified period, usually one year. The event could be anything with the potential to cause the loss of or damage to an asset or population."
- **"Vulnerability (V)** - The probability that, given an adverse event, the estimated consequences will ensue."
- **"Consequence (C)** - The outcomes of an event occurrence, including immediate, short and long-term, direct, and indirect losses and effects. Loss may include human fatalities and injuries, economic damages, and environmental impacts, which can generally be estimated in quantitative terms, and less tangible, non-

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quantifiable effects, including political ramifications, decreased morale, reductions in operational effectiveness, or military readiness, etc.

This approach has been used in multiple sectors, including water and wastewater. The American Water Work Association (AWWA) developed its Risk and Resilience Management of Water and Wastewater System Standard (J-100) (AWWA, 2010) based on the RAMCAP framework.

Since quantitative risk assessments are a reasonably new approach, this method is not widely used in the transportation sector. However, some transportation agencies, including state DOTs have begun incorporating this approach. Some of the state DOTs that have implemented this approach include Minnesota, Nevada, New York, Utah, Virginia, Washington, and Colorado (Caltrans Division of Research, Innovation and System Information, 2015).

The Colorado Department of Transportation (CDOT) first implemented this methodology to "build back batter" after a 2013 major flood event. This work continued with a pilot project sponsored by FHWA to estimate the annual risk from multiple threats to highway assets on I-70 (AEM Corporation, 2017). Following this pilot, CDOT invested in the development of a Risk and Resilience Procedure (AEM Corporation, 2020) to help guide CDOT staff on the calculation of risk and resilience to multiple highway assets, including culverts, bridges, and roadways from multiple threats such as flood, scour, rockfall, and post-fire debris flow (see Figure 12).

Similarly, Utah DOT was also sponsored by FHWA Extreme Weather and Climate Change Vulnerability Assessment to develop a pilot project which also implemented the RAMCAP framework and methodology to estimate the risk to their highway infrastructure on US-40 from multiple applicable threats.

Washington State was an early adopter of the qualitative methods, beginning the development of a formal risk assessment process in 2002. Nevada DOT implemented its version of a qualitative method in 2008 and New York State DOT in 2009. Utah DOT started by investigating WSDOT qualitative methods and then implementing their program. Minnesota DOT began implementing these practices in 2013 and Virginia in 2011 (Caltrans Division of Research, Innovation and System Information, 2015).

Some states, like Minnesota, Nevada, New York, Utah, and Washington, have similar qualitative risk assessment methods. They start with a workshop to identify and quantify risks. They then utilize a tool to assess the data gathered and conduct a follow-up to track risk throughout a project's development.

In Minnesota, projects identified as "major projects" are subject to quantitative risk analysis requiring a consultant-led analysis workshop to identify project risks. MnDOT utilizes the @RISK tool by Palisade to identify probabilities and risks associated with

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alternatives (Caltrans Division of Research, Innovation and System Information, 2015). Most projects subjected to Nevada's comprehensive quantitative risk analysis are large projects that start with a facilitated workshop. They utilize a risk management tool that generates probabilistic modeling and risk registers. Utah uses qualitative and quantitative tools to assess risk during project development, typically as early as possible. For many states, like Washington and Virginia, one of the key outputs of their qualitative risk assessment is a risk register.

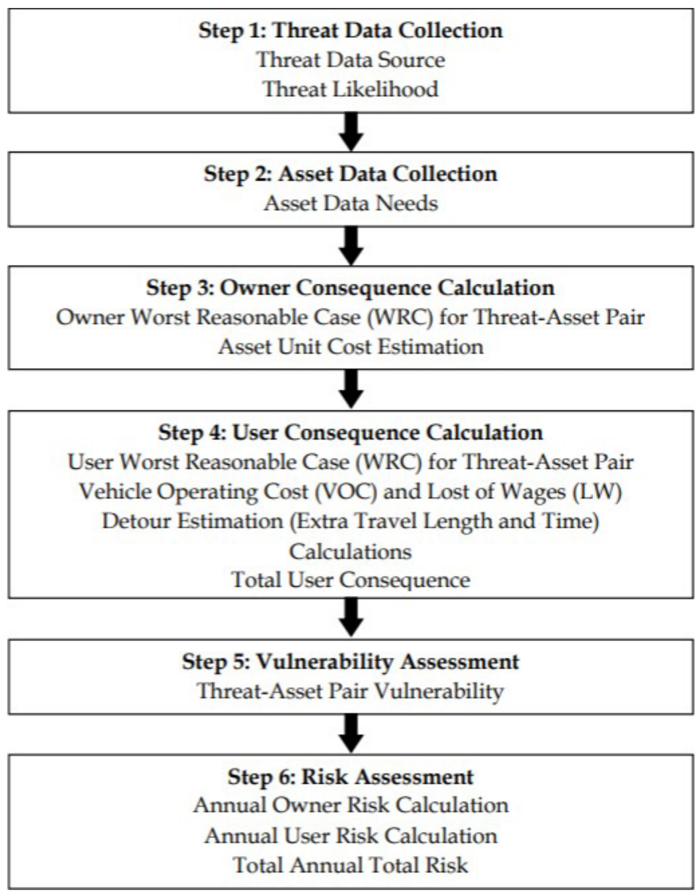

Figure 12. CDOT Risk Assessment Procedure

While states have noted challenges to getting their qualitative risk assessment programs off the ground, there are benefits resulting from using this new method. NDOT cites significant cost saving, MnDOT has found cost estimates are closer to or under budget, UDOT has benefitted from the increased communication due to the workshops, and WSDOT believes it better assist in addressing issues that arise in the field (Caltrans Division of Research, Innovation and System Information, 2015).

Probabilistic models attempt to account for uncertainty by employing random variables with their respective probability distributions to produce a set of possible outcomes for every risk calculation.

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Deterministic models are entirely determined by their parameter values and initial conditions. However, natural phenomena are stochastic in nature. Probabilistic models share greater fidelity with biological processes, capture uncertainty, and quantify risk using values from the physical world. Probabilistic approaches include Bayesian Belief Networks, Markov chains, and Monte Carlo simulation. These models are recommended when there is a certain degree of uncertainty on the parameters used to calculate vulnerability or risk.

The European Union developed an example of a probabilistic risk assessment model named INFRARISK to evaluate risks to multiple infrastructure networks from multiple threats (INFRARISK, n.d.). This model uses Monte Carlo simulations, which use random sampling for a given variable to generate a set of possible numerical results. For example, INFRARISK uses Monte Carlo simulation to estimate the probability of ground motions (earthquakes).

Examples of transportation agencies in the U.S employing probabilistic methods include 1) the partnership between Arizona Water Science Center (AZWSC) and the Arizona DOT and 2) the Mechanistic Empirical Pavement Design Guide (MEPDG)

The partnership between AZWSC and ADOT has resulted in improved stormwater management. This includes data collection and modeling at key water crossings to provide data on flood magnitude and measure changes in cross-sectional area to refine the accuracy of hydrologic models and how channel conditions affect infrastructure. This partnership between AZWSC and ADOT led to a rapid installation of gauges and sensors to monitor hydrologic parameters, including stormwater runoff, peak flow, velocity, and topographic surveys to improve bank stabilization projects and bridge and culvert design. A GIS Resilience Database was created to identify areas at risk, using data collection and new technology for proactively addressing asset management issues. As part of its 2019 resilience pilot project (AzDOT, 2019), AZDOT developed a quantitative probabilistic methodology for bridge asset class considering resilience in infrastructure life-cycle management.

The MEPDG was used to develop a probabilistic pavement fragility model for generating fragility functions, which integrates flood hazards, pavement structure, pavement performance, and damage states (Lu, Tighe, & Xie). NCHRP Report 602 documents the calibration and validation of the Enhanced Integrated Climatic Model (EICM), a one-dimensional coupled heat and moisture flow program intended to analyze pavement-soil systems for Pavement Design (Zapata & Houston, 2008).

4.1.3 Hybrid Risk Assessments Methods

Hybrid methods are a combination of qualitative and quantitative methods. The World Health Organization (WHO) (2009) (WHO, 2009) explains that semi-quantitative risk

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assessment bridges the gap between purely descriptive measures of risk and numerical measures using a scoring system.

A common semi-quantitative method is the multi-criterion weighted index model. Multi-criterion, weighted index models are frequently used in GIS to map hazard susceptibility or to identify sites most suitable for land use. A multi-criterion risk model calculates risk as to the sum of the products of individually ranked criteria (see Equation 2) (Stanujkic & Zavadskas, 2015).

$$R = \sum_{i=1}^{n} W_i \; x \; C_i$$

Equation 2. Weighted Multi-Criteria Model

Where:

R = total relative risk

W_i = weighting

C_i = criterion

This type of model falls under the umbrella of relative risk models because the selection of criteria and the ranking and weight are subjectively selected. There are different ways to generate the weighting criterion in these models, either expert opinion or more sophisticated methodologies. For example, if the slope is three times as important as geology (rock type), the slope weighting criteria may be assigned a weighting value of 3, while geology is given a weighting value of 1.

An example of a hybrid model is the FHWA Vulnerability Assessment and Adaptation Framework (VAAF) (Filosa, Plovnick, Miller, & Pickrell, 2017) where vulnerability is scored as a function of multiple components (exposure, sensitivity, and adaptive capacity). Users can adjust the scoring by assigning weights to those parameters.

Two tools have been implemented to help transportation agencies put the VAAF into practice, the Vulnerability Assessment Scoring Tool (VAST) and the Coupled Model Intercomparing Project (CMIP) Climate Data Processing Tool. Both tools have been used extensively by state DOTs and MPOs in FHWA-sponsored risk and resilience pilot studies.

The first tool, VAST, is a spreadsheet tool that guides planners to conduct a vulnerability screen of their assets (Adaptation Clearing House, 2015). This tool uses an indicator-based approach to determine how assets will respond to climate stressors and results in a weighted vulnerability score. There are three components of vulnerability measured:

- **Exposure** – whether an asset will experience a given stressor.

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- **Sensitivity** – whether an asset will be damaged or disrupted by a given stressor. The worse an asset's condition, the more likely it will be damaged if exposed.
- **Adaptive capacity** – How well the system can cope with damage or disruption to specific assets. This is influenced by data such as usage statistics or traffic volumes.

The outputs of this tool can be used as a component of the calculation of vulnerability used in either a probabilistic or deterministic risk assessment model.

The second tool, the CMIP Climate Data Processing Tool 2.1, is an online web application that assists planners in downloading data from the World Climate Research Programmer's CMIP (CMIP) databases and processing that data into statistics relevant to transportation planners (FHWA, 2020). Users start by accessing the CMIP database (Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections, n.d.) and following the tool's instructions to download data on specific grids that encompass the locations they are interested in examining. The tool processes the downloaded climate data to produce a variety of climate-related statistics related to events like heat, cold, and precipitation that can be used to estimate the impact of different risks.

Another example of a risk assessment model that uses assigned scores to multiple parameters was developed by Pennsylvania DOT as part of an extreme weather vulnerability study and climate change adaptation initiatives. Figure 13 shows the scoring methodology and risk equation developed for this project (PennDOT, 2017).

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Variable	Source	Scoring Methodology
Sensitivity to Flooding based on 4-Day Precipitation Total (*Historic Analysis Only*)	NOAA Climate Data Online	• ≤ 1.5 inch = 10 • ≤3 inches = 7.5 • ≤5 inches (or for comment locations) = 5 • ≤7 inches = 2.5 • > 7 inches = 1
Average Depth (*Future Analysis Only*)	*Pilot Study Analyses for Allegheny, Delaware and Lycoming Counties*	• < 3 Inches = 1 • < 5 inches = 2.5 • < 9 inches = 5 • < 12 inches = 7.5 • > 12 inches= 10
Floodplain	PASDA Floodplain	• Yes = 10 • No = 0
Overall Pavement Index	RMSSEG	• Excellent = 2.5 • Good, Other = 5.0 • Fair = 7.5 • Poor = 10.0
Scour Critical Bridges	BMS 2	• Yes = 10 ; • No = 0
Deficient Pipes	RMSPIPE	• Yes = 10 ; • No = 0
Two-Way Volume	RMSTRAFFIC	• < 5,000 = 1 • < 10,000 = 2 • < 15,000 = 3 • < 20,000 = 4 • < 25,000 = 5 • < 30,000 = 6 • < 35,000 = 7 • < 40,000 = 8 • < 45,000 = 9 • > 45,000 = 10
Two-Way Truck Volume	RMSTRAFFIC	• < 500 = 1 • < 1,000 = 2 • < 2,000 = 3 • < 3,000 = 4 • < 4,000 = 5 • < 5,000 = 6 • < 6,000 = 7 • < 7,000 = 8 • < 8,000 = 9 • > 8,000 = 10
Functional Class	RMSADMIN	• Local = 1 • Collector or Minor Arterial = 2.5 • Other = 5 • Principal Arterial = 7.5 • Interstate = 10
Included as PennDOT Official Detour Route	*Shapefiles provided by PennDOT GIS Department*	• Yes = 10 ; • No = 0

Risk Cumulative Score =

3 x (Precipitation Score or Average Depth x 0.5 + Floodplain Score x 0.5) +

3 x (OPI Score x 0.4 + Scour Score x 0.4 + Pipe Score x 0.2) +

4 x (Volume Score x 0.4 + Functional Class Score x 0.3 + Detour Score x 0.1 + Truck Volume Score x 0.2)

Figure 13. PennDOT Risk Assessment Model and Cumulative Scoring Formula (PennDOT, 2017)

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4.1.4 Risk Metrics

Since there is no standard risk assessment methodology, there are no standard risk metrics, especially in the transportation sector.

In the field of economics, Holton (2014) (Holton, 2014) distinguished between risk measures – "the operation that assigns a value to a risk" and risk metrics – "the attribute of risk that is being measured." and stated that risk metrics commonly take one of the following three forms: those that quantify exposure, uncertainty, or exposure and uncertainty in some combined manner.

Depending on how risk is determined, qualitative, quantitative, or both, the metrics used to quantify risk may vary. Table 6 describes some examples of risk metrics for measuring economic and population risk (Westen, Kingma, Damen, Kerle, & Alkema, 2011).

Table 6. Different Ways of Expressing Risk

<table>
<tr><th>Type</th><th>Sub-Type</th><th colspan="2">Principle</th></tr>
<tr><td rowspan="2">Qualitative</td><td>Qualitative</td><td colspan="2">Based on relative risk classes categorized by expert judgment. Risk classes: High, Moderate, and Low</td></tr>
<tr><td>Semi-quantitative</td><td colspan="2">Based on relative ranking and weights assignments by criteria. Risk index: ranked values (0-1, 0-10 or 0-100). (dimensionless)</td></tr>
<tr><td rowspan="6">Quantitative</td><td>Probability</td><td colspan="2">Probabilistic values (0-1) for having a predefined loss over a particular time period</td></tr>
<tr><td rowspan="4">Economic Risk</td><td colspan="2">Quantification of the expected losses in monetary values over a specific period of time</td></tr>
<tr><td>Probable Maximum Loss (PML)</td><td>Probable Maximum Loss (PML) The largest loss believed to be possible in a defined return period, such as 1 in 100 years, or 1 in 250 years.</td></tr>
<tr><td>Average Annual Loss (AAL)</td><td>Expected loss per year when averaged over a very long period (e.g., 1,000 years). Computationally, AAL is the summation of products of event losses and event occurrence probabilities for all stochastic events in a loss model.</td></tr>
<tr><td>Loss Exceedance Curve (LEC)</td><td>Risk curve plotting the consequences (losses) against the probability for many different events with different return periods.</td></tr>
<tr><td></td><td colspan="2">Quantification of the risk to the population</td></tr>
</table>

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	Population risk	Individual risk	The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by a hazard; or follows a particular pattern of life that might subject him or her to the consequences of a hazard.
		Societal risk	The risk of multiple fatalities or injuries in society as a whole. Society carry the burden of a hazard that causes deaths, injury, financial, environmental, and other losses.

A common example of qualitative risk metrics is presented in Figure 14, where risk is estimated using risk matrices and reported ranging from "Low" to "High." Figure 14 and Figure 15 present examples of risk matrices for a 2015 FHWA pilot project to estimate risk for the Central Texas regional transportation infrastructure (Cambridge Systematics and ICF International, 2015).

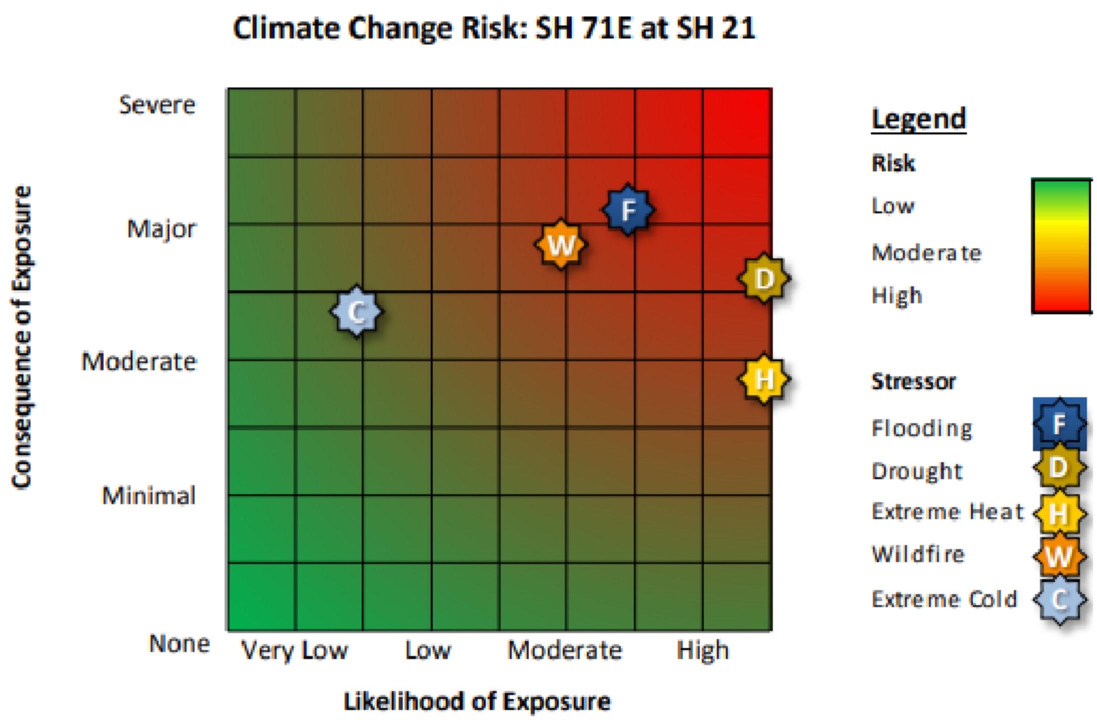

Figure 14. Climate Change Risk Matrix, 2015 Central Texas Extreme Weather and Climate Vulnerability Study (Cambridge Systematics and ICF International, 2015) (Winter, et al., 2014)

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ID	Asset	Flooding	Drought	Heat	Wildfire	Extreme Cold
2	MetroRail Red Line at Boggy Creek	Moderate-High	Inconclusive	Moderate	None	Low-Moderate
3	SH 71E at SH 21	High	Moderate-High	Low-Moderate	Moderate-High	Low-Moderate
4	I-35 at Onion Creek Parkway	Low	None	None	Moderate-High	Low-Moderate
5	US 290W/SH 71 - Y at Oak Hill	Moderate	Moderate	None	High	Low
6	Loop 360/RM 2222	Moderate	Moderate	None	High	Low-Moderate
7	FM 1431 at Brushy Creek/Spanish Oak Creek	None	Moderate	Low	Moderate-High	Low
8	US 281 and SH 29 Intersection	Moderate-High	Low	Low	Moderate	Low
9	US 183 north of Lockhart	Low-Moderate	High	Low-Moderate	Moderate-High	Low-Moderate
10	SH 80 (San Marcos Highway) at the Blanco River	Moderate	Low	Low	Moderate	Low

Figure 15. Risk Rating Summary for the 2015 Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure (Cambridge Systematics and ICF International, 2015)

As an example of a quantitative risk metric, the ASME's RAMCAP Plus[SM] (ASME, 2009) methodology for risk assessment measures risk as to the product of threat likelihood, vulnerability, and consequences. Since these parameters can be estimated as probabilities (or percentages) for exposure and threat likelihood and in dollars for consequences, the product provides a risk result in dollars.

As mentioned previously, Colorado DOT and Utah DOT adopted the RAMCAP Risk calculation methodology to estimate the risk to their highway infrastructure from multiple threats and use risk metrics represented in dollars per year (e.g., annual risk for culverts from flooding ($/year)).

Moreover, The Virginia Transportation Research Council (2002) (Ferguson, 2002) identified four risk metrics for describing the consequences of storm surge and high winds:

- Ratio of repair cost to reconstruction cost
- Repair cost
- Time to recover
- Cost to industry

In the rail sector, The Federal Rail Administration (FRA) describes risk metrics as the "primary quantitative inputs for quantitative risk analysis related to hazmat

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transportation safety." The risk metrics (see Table 7 (Federal Rail Administration, 2015)) are conditional probabilities of accident likelihood used as inputs to a fault-tree analysis.

Table 7. Risk Metrics, FRA (Federal Rail Administration, 2015)

Risk Metric	Function of
Train accident frequency	Accident cause, FRA Track Class, Railroad Type (Class I or non-Class I)
Car derailment probability	Train speed, train length, loading
The conditional probability of a car containing hazmat	Relative volumes of freight and hazmat shipments on route being analyzed
Conditional probability of release from derailed car	Tank car design/construction, train speed, accident cause
Conditional probability of harm from release	Hazmat type, emergency response action

4.1.5 Risk-based Performance Measures

Different performance measures and targets are used in transportation. Transportation agencies use these to measure how their agencies perform over time and if they are achieving their set targets. Performance measures (goals or key performance indicators (KPI)) must be distinguished from performance metrics. Performance metrics are the numbers or qualitative characteristics within a performance measure that help track performance and progress.

For example, US DOT's Fiscal Year 2017 Annual Performance Report lists under the goal of roadway safety the following performance measure: "highway fatality rate per 100 million vehicle-miles traveled) with the target number of fatalities being 1.02 (US DOT, D.C.). This performance measure contains two metrics –the number of fatalities and the millions of miles traveled.

MAP-21 requires transportation agencies to develop a risk-based performance management asset management plan to be reviewed every four years [3]: the stated purpose of MAP-21 is the "establishment of a performance-and-outcome-based program (FHWA, 2013). Table 8 lists seven goal areas and their respective national goals for the transportation sector, as cited in §1203: 23 USC 150(b).

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Table 8. MAP-21 Goal Areas and National Goals

Goal area	National goal
Safety	To achieve a significant reduction in traffic fatalities and serious injuries on all public roads.
Infrastructure condition	To maintain the highway infrastructure asset system in a state of good repair.
Congestion reduction	To achieve a significant reduction in congestion on the National Highway System
System reliability	To improve the efficiency of the surface transportation system
Freight movement and economic vitality	To improve the national freight network, strengthen the ability of rural communities to access national and international trade markets, and support regional economic development
Environment sustainability	To enhance the performance of the transportation system while protecting and enhancing the natural environment
Reduced project delivery delays	To reduce project cost, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including regulatory burdens, and improving agencies' work practices

Further, §1203; 23 USC 150(c) lists the following performance measures.

- Pavement condition on the Interstate System and on the remainder of the National Highway System (NHS)
- Performance of the Interstate System and the remainder of the NHS
- Bridge condition on the NHS
- Fatalities and serious injuries—both number and rate per vehicle mile traveled--on all public roads

- Traffic congestion
- On-road mobile source emissions
- Freight movements on the Interstate system

Along with the requirements from MAP-21, AASHTO also provides a series of performance measures in their *Transportation Asset Management Guide- A Focus on Implementation.* The performance measures included in the guide are:

- Condition
- Life-cycle cost
- Safety
- Mobility
- Reliability
- Customer measures
- Externalities
- Risk

To track success in meeting these goals, State DOTs establish their performance measures, typically outlined in the Transportation Asset Management Plan (TAMP). Here are some examples:

- Washington State DOT tracks percentage of pavement that falls within a given condition state, for example, the rate of pavement (all state roads) in fair or better condition with a target of 85% (Miller, 2018).
- Minnesota DOT's performance measures for operational excellence includes the percentage share of the Interstate System with poor ride quality in the travel lane, with a target of no more than 2% (MnDOT, 2018).
- UDOT's performance measure for signal systems is 95% of the systems are rated as average or in good condition (UDOT, 2019).
- Arizona DOT's performance target for NHS bridges is 52% of bridges classified as in good condition (2- and 4-year targets) (Anderson, 2019).

Flannery et al. found that information needed to develop resilience metrics and assessment methods was a "pressing need" for state DOTs (Flannery, Development and incorporation of quantitative risk and resilience analysis standards into agency decision making, 2019). After reviewing the planning documents of 101 MPOs and 50 state DOTs, Dix et al. found that only 5 state DOTs established resilience-related performance measures compared to 19 MPOs. In addition, state DOT performance measures tended to be tied to safety and security, environmental stewardship, or system preservation (asset management) and did not address natural hazards or extreme events. In contrast, 19 MPOs included performance measures directly related to promoting resilience against climate change and extreme events. Table 9 gives example performance measures for adaptation to climate change for 9 MPOs. (Asam, Bhat, Dix, Bauer, & Gopalakrishna, 2015) adapted a list of sample operations and performance measures

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from FHWA's desk reference, *Advancing Metropolitan Planning for Operations* (FHWA, 2010), for possible use as objectives and measures for improving resilience to climate change (see Table 10).

Given that resilience has an inverse relationship with risk (see the section on the relationship between risk and resilience), i.e., increasing resilience decreases risk, the performance measures listed in Table 9 and Table 10 could serve as examples for risk-based performance metrics.

The transportation sector has identified the need to incorporate risk and resilience into performance measures (risk-based performance measures); however, there is still no standard process or measure.

Table 9. MPO Performance Measures

MPO	Goal or Objective	Performance Measure(s) or Targets
Cape Cod MPO (MA) (Cape Cod MPO, 2015)	Improve the transportation system's resiliency to the effects of sea-level rise.	Evaluate potential impacts of sea-level rise for all TIP projects during the 25% design review, and adjustments to projects are made as warranted.
	Improve stormwater management and treatment in transportation improvement projects.	Provide improved stormwater management and treatment to 50% of TIP projects outside of sensitive areas and 100% of TIP projects within sensitive areas.
Hillsborough County MPO (Tampa, FL) (Hillsborough County MPO, 2016)	Increase the security and resiliency of the multimodal transportation system.	Protect low-lying major roads from storm surge and flooding Maintain stormwater drainage programs.
Merrimack Valley MPO (Haverhill, MA) (Merrimack Valley MPO, 2015)	Adaptive planning for climate change.	Number of coastal communities with adaptation plans.
Miami-Dade MPO (FL) (Miami-Dade MPO, 2014)	Reduce the vulnerability and increase the resiliency of critical infrastructure to the impacts of climate trends and events.	Number of highway lane and centerline miles within the 100-year floodplain.

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MPO	Goal or Objective	Performance Measure(s) or Targets
Mid-Region COG (Albuquerque, NM) (Mid-Region COG, 2015)	Environmental resilience: Prepare for climate uncertainties.	Development in high flood risk areas: Employment and housing in FEMA 100-Year floodplains. Development in forest fire risk areas: Employment and housing in wildland-urban intermix areas.
Northern Middlesex MPO (Lowell, MA) (Northern Middlesex MPO)	Protect critical infrastructure from the effects of climate change and address stormwater runoff and flooding concerns.	Number of stormwater improvement projects implemented by local communities and MassDOT.
Palm Beach MPO (FL) (Palm Beach Metropolitan Planning Organization., 2014)	Provide an efficient and reliable vehicular transportation system.	Increase the percentage of facilities that accommodate two feet sea level rise; the performance target is 90% for the strategic intermodal system network in 2025.
Regional Planning Commission (New Orleans, LA) (Regional Planning Commission, 2015)	Environmental sustainability: implement projects that consider the impacts of climate change and natural hazard mitigation.	Number of projects that raise the roadway grade or increase resilience against climate change or natural disasters through other means (tracked annually).
Tri-County Regional Planning Commission (Peoria, IL) (Tri-County Regional Planning Commission, 2015)	Efficient and resilient transportation system.	Ensure 95% of all roadways have a volume-capacity ratio less than one by 2020. Reduce the percentage of roadways in "poor" or "fair" condition. Reduce the percentage of roadways in "critical backlog." Reduce commute times by 2.5% by 2025.

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Table 10. Sample Operations Objectives and Performance Measures

Category	Operations Objectives	Performance Measures
Clearance Time (Weather-Related Debris)	Reduce average time to complete clearing (mode, hierarchy of facilities, or subarea of region) of weather-related debris after weather impact by X percent in Y years. Reduce average time to complete clearing (interstates, freeways, expressways, all roads, main tracks, and main sidewalks) of weather-related debris after weather impact by X percent in Y years.	Average time to clear selected surface transportation facilities of weather-related debris after weather impact.
Detours for Impacted Roadways	Increase by X percent the number of significant travel routes covered by weather-related diversion plans by year Y. Increase the percentage of agencies that have adopted multi-agency weather- related transportation operation plans and that are involved in transportation operations during weather events to X percent by year Y.	Percentage of significant travel routes covered by weather- related diversion plans. Percentage of agencies involved in transportation operations during weather events that have adopted multi-agency, weather-related transportation operations plan.
Disseminating Information	Reduce time to alert travelers of travel weather impacts (using variable message signs, 511, Road Weather Information Systems [RWIS], public information broadcasts, the agency's website, Web 2.0 technologies, etc.) by X (time period or percent) in Y years.	Time from beginning of weather event to posting of traveler information on (variable message signs, 511, RWIS, public information broadcasts, etc.). Time from beginning of weather event to posting of traveler information on agency website.
	Increase the percentage of major road network (or transit network	Percentage of major road (transit or bicycle) network

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Road Weather Information System Coverage	or regional bicycle network) covered by weather sensors or an RWIS by X percent in Y years as defined by an RWIS station within Z miles.	within Z miles of an RWIS station.
Signal Timing Plans	Special timing plans are available for use during inclement weather conditions for X miles of arterials in the region by year Y.	Number of miles of arterials that have at least one special timing plan for inclement weather events.

4.2 Resilience Assessment Methodologies and Metrics

Federal initiatives such as MAP-21 and the FAST-ACT compel transportation agencies to assess the resilience of their systems. In a frequently cited paper, Bruneau (2002) (Bruneau & Reinhorn, Overview of the resilience concept, 2006) outlined the four "R's" of resilience: robustness, redundancy, resourcefulness, and rapidity.

- **Robustness**— "Strength, or the ability of elements, systems, and other measures of analysis to withstand a given level of stress or demand without suffering degradation or loss of function."
- **Redundancy**— "The extent to which elements, systems, or other measures of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of a disruption, degradation, or loss of functionality."
- **Resourcefulness**— "The capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other measures of analysis."
- **Rapidity**— "The capacity to meet priorities and achieve goals in a timely manner to contain losses, recover functionality and avoid future disruption."

Note that these metrics align with FHWA's sensitivity and adaptive capacity concepts. Other suggested metrics for the four "R's" relevant to transportation can be found in Table 11 (Parkany & Ogunye, 2016).

An exhaustive study of transportation metrics was completed by Sun et al. (2018), describing three categories of metrics: topological, traffic-related, and functional (see Table 12) (Sun, Bocchini, & Davison, 2018). Topological might be regarded as measures of redundancy, one of the four "R's." Traffic-related metrics assess network performance by measuring the amount of traffic flowing through the network. Functionality metrics involve a before and after comparison of network performance and evaluate the network's ability to resume normal functionality after a disruption. For example, the resiliency triangle (see Figure 16 (Bruneau, Chang, Eguchi, & Lee,

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2003)) shows that a system is fully functional before an event. Functionality drops dramatically immediately following an event, followed by a gradual return to full functionality.

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Table 11. Resilience Metrics for Transportation

Resilience Pillar	Indicator
Robustness	Hours of congestion Spatial extent of congestion Travel time index Optimal spare capacity Pavement condition Weather impact Volume of congestion
Redundancy	Distance to alternative routes Percentage of corridor(s) with alternate routes Available capacity on alternative routes Congestion on alternative routes Graph theory connectivity score Transit alternatives Adjacent park & ride lots
Resourcefulness	Safety service patrol Average incident duration Availability of special transportation funding Message signs Weather stations The use of alternative routes Construction projects Weather mitigation capability
Rapidity	Regain time for top 5% incident Average construction project duration

Figure 16. The Resiliency Triangle, adapted from (Bruneau, Chang, Eguchi, & Lee, 2003)

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Table 12. Resilience Metrics

Class	Metric		Description
Topological	Centrality		Measure of influence of a node in a network.
	Weighted Centrality		Same as Centrality except links between nodes are weighted. Weights are typically based on link length, travel time or travel distance.
Traffic	Travel time		Travel time used to measure travel delay during and post-event.
	Throughput		The total sum of flows of shipments/passengers between origins and destinations.
	Congestion Index		A measure of travel delays due to a disruption, e.g., link delay to acceptable travel time.
Functionality	Resilience Triangle		A graph of functionality recovery starting from the extreme event until full recovery.
	Resilience Index		Based on the resilience triangle, a measure of functionality over time.
	Capacity	Absorptive	Ability to absorb perturbations from an event.
		Adaptive	Ability of system to gradually adapt itself to a disruption.
		Coping	Ability to respond to and recover from events.
		Restorative	Ability to bounce back to the original performance level or better.

Other metrics of resilience have been developed and used in the transportation sector. An example includes a qualitative metric developed by AEM corporation called Level of Resilience Index (LOR) which is based on criticality scores of a system or network (low, medium, or high) and the cumulative annual risk of the system from multiple threats estimated in dollars per year (see Figure 17). Figure 18 shows an example of the application of this metric on Colorado DOT's I-70 Pilot, where the LOR Index varies

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from A through E, where LOR A means the system or network has a "Very High" resilience and LOR E means it has a "Very Low" Resilience (AEM Corporation, 2017).

Annual Risk (Robustness/Rapidity)	Criticality for Systems Operations (Resourcefulness/Redundancy)		
	Low	Moderate	High
0-20% Cumulative Annual Risk	A	B	C
21-40% Cumulative Annual Risk	B	B	C
41-60% Cumulative Annual Risk	C	C	C
61-80% Cumulative Annual Risk	C	C	D
81-100% Cumulative Annual Risk	D	D	E

Figure 17. Level of Resilience (LOR) Matrix, from CDOT I-70 Corridor Risk and Resilience Pilot (AEM Corporation, 2017).

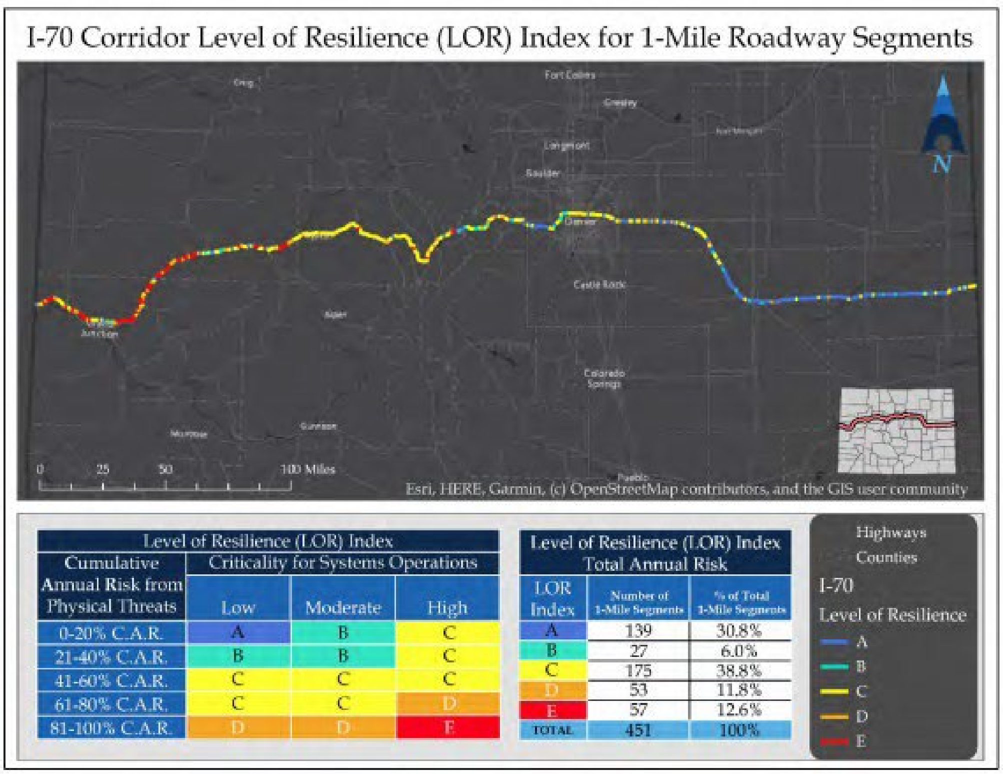

Figure 18. Example of Application of LOR Index on CDOT's I-70 Risk and Resilience Pilot (AEM Corporation, 2017).

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Utah DOT also developed a resilience assessment metric as part of its risk management process. Noting that resilience is "inversely proportional to risk and criticality," Utah DOT formulated the following equation (see Equation 3) (Alder, et al., 2020). UDOT's resilience metric also demonstrates the relationship between risk and resilience.

$$Resilience = 1/(risk \times criticality)$$

Equation 3. Resilience Metric

In summary, researchers and practitioners have developed several metrics to estimate the risk and resilience of transportation networks. However, there is still no agreement on assessment methodology, standard metrics, or performance indicators. The National Academy of Science, Engineering and Medicine recently established a full committee named Transportation Resilience Metric to help identify and examine these metrics (The National Academy of Sciences, Engineering and Medicine, n.d.).

5 Major Components of a Risk Assessment Methodology

This section discusses the major components of a risk assessment methodology: asset characterization (criticality), threat assessment, vulnerability assessment, and consequence modeling.

5.1 Methods to Identify Critical Transportation Assets

Determining asset criticality is one of the first steps in risk and resilience analysis, "Asset Characterization." Criticality is a measure of the importance of an asset to the system'. ICF International's report for USDOT, *Assessing Criticality in Transportation Planning*, (ICF International, 2014) describes criticality in the context of climate change vulnerability assessments as "…those assets of "greatest importance," such as assets that are of economic importance, provide access to healthcare facilities, serve as emergency evacuation routes, provide social connectivity, have cultural significance, or support other core values."

The ICF International report (ICF International, 2014) describes three approaches for assessing criticality: 1) desk review, 2) stakeholder elicitation, and 3) hybrid approach.

- **Desk review**: This approach is essentially an index method that quantitatively compares and ranks assets based on a set of criteria, such as AADT, functional class, network redundancy, etc. (ICF International, 2014; Hampton Roads Transportation Planning District Commission, 2014). Example risk and resilience studies that employed this approach include Virginia DOT's Hampton Roads pilot, which used traffic volume, proximity to a hurricane evacuation route, location on a maintenance route, and relative elevation compared to mean sea level, and New Jersey's pilot which based its criticality assessment on the importance of destinations (population density and jobs), traffic volume, and the emergency function of routes (Cambridge Systematics, 2011; ICF International, 2014).

- **Stakeholder elicitation**: This approach assembles stakeholders and subject matter experts to participate in one or more workshops to elicit expert opinions on which assets are critical. For example, for Washington State DOT's pilot study, Operations and Maintenance (O&M) personnel and engineers participated in workshops to rank asset criticality on a scale of 1 to 10, based on such factors as AADT, functional class, availability of alternate routes, and whether part of the National Highway System (NHS) (ICF International, 2014; WSDOT, 2011).
- **Hybrid approach:** This approach combines the desktop review with stakeholder elicitation. Typically, analysts begin by ranking assets based on various criteria and then solicit expert opinions from SMEs and stakeholders to get feedback on the selection of criteria, weightings, rankings, etc. (ICF International, 2014). Table 13 is an example of a weighted, multi-criterion index model. The criteria include AADT (non-truck), freight (truck AADT), functional classification, and tourism revenue, binned into 5 quantiles where each quantile is assigned an index value from 1 to 5. The criticality score for a given transportation facility is the sum of the indices for each criterion.

Table 13. Example Multi-Criterion Criticality Table

	Criticality Score					
Criteria	1 Very Low Impact	2 Low Impact	3 Moderate Impact	4 High Impact	5 Very High Impact	Weight
AADT	<= 1,000	1,101 - 5,000	5,001 - 10,000	10,001 - 15,000	>15,000	20%
Freight	<= 500	500 - 1,000	1,001 - 5,000	5,001 - 10,000	>10,000	20%
AASHTO Road Class	Minor Collectors	Major Collectors	Minor Arterial	Principal Arterial	Interstate	20%
Tourism ($M)	<50	51-100	101 - 150	151 - 200	>200	20%

Different approaches to identify asset criticality can be developed and have been used and tailored to different agency needs.

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5.2 Threat Assessment and Incorporation of Uncertainty

Another important step of risk and resilience analysis is threat assessment. The elements of threat assessment include threat likelihood (probability of occurrence), magnitude or severity, and extent. The first step is to identify the threats relevant to a given study area. The next step is threat modeling to determine the frequency and magnitude of the threats that have been identified. This section addresses the methodologies and data needs for completing a threat assessment.

5.2.1 Threat Identification

Identifying the threats of concern to a community can be accomplished by reviewing historical records, disaster declarations, hazard maps, and subject matter opinions.

Although by no means exhaustive, Table 14 provides a list of natural, technological, and human-caused threats that have been identified by many states (DHS, 2012). Natural threats result from earth system processes, such as floods, earthquakes, and landslides. Technological hazards are due to accidents or the failure of man-made systems, such as power failures or train derailments. Finally, human-caused threats include intentional acts, such as sabotage and cyber-attacks. Naturally, the task is to determine which amongst these is relevant to the jurisdiction of concern. This task can be accomplished with the help of hazard maps.

Table 14. Table of Threats/Hazards and Examples

Natural	Technological	Human-caused
Resulting from acts of nature	Involves accidents or the failures of systems and structures	Caused by the intentional actions of an adversary
• Flood • Earthquake • Avalanche • Debris flow • Wildfire • Pandemic • Drought • Epidemic • Hurricane • Landslide • Tornado	• Airplane crash • Dam/levee failure • Hazardous materials release • Power failure • Radiological release • Train derailment • Urban conflagration • Bridge strikes	• Civil disturbance • Cyber incidents • Sabotage • Terrorist acts

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Natural	Technological	Human-caused
• Tsunami • Volcanic eruption • Winter storm • Extreme temperature		

The relevancy of a hazard to a study area is dependent upon geography, climate, population density, proximity to infrastructure, etc. Using GIS to overlay hazard maps such as USGS landslide inventories (USGS) (see Figure 19), FEMA National Flood Hazard Layer (NFHL) (FEMA, 2021) (see Figure 20), and NOAA's historical tornado track database (NOAA, 2022) (see Figure 21), over infrastructure is an effective way to identify relevant threats and isolate exposed assets. The spatial intersection of hazard maps and assets helps define the threat-asset pairs that warrant further analysis.

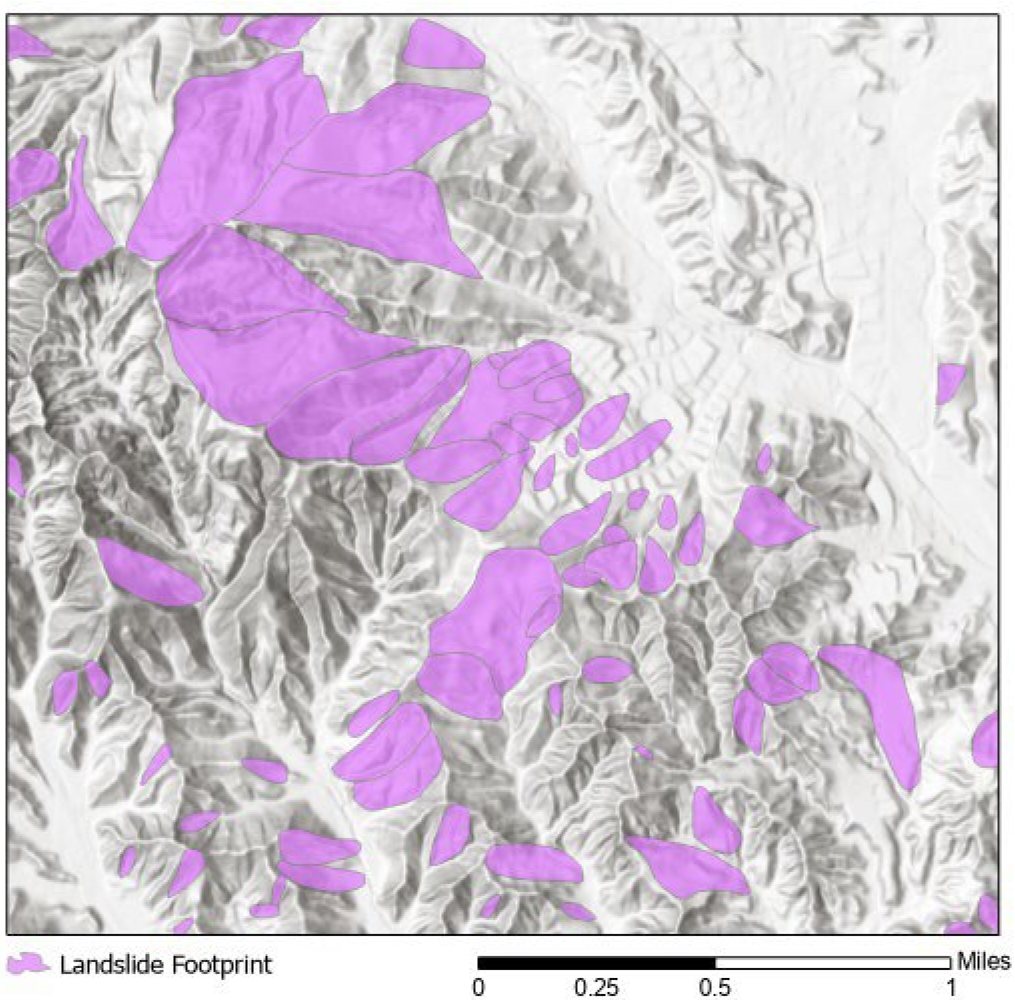

Figure 19. Landslide Inventory, West of Santa Barbara, CA – Data from USGS (USGS)

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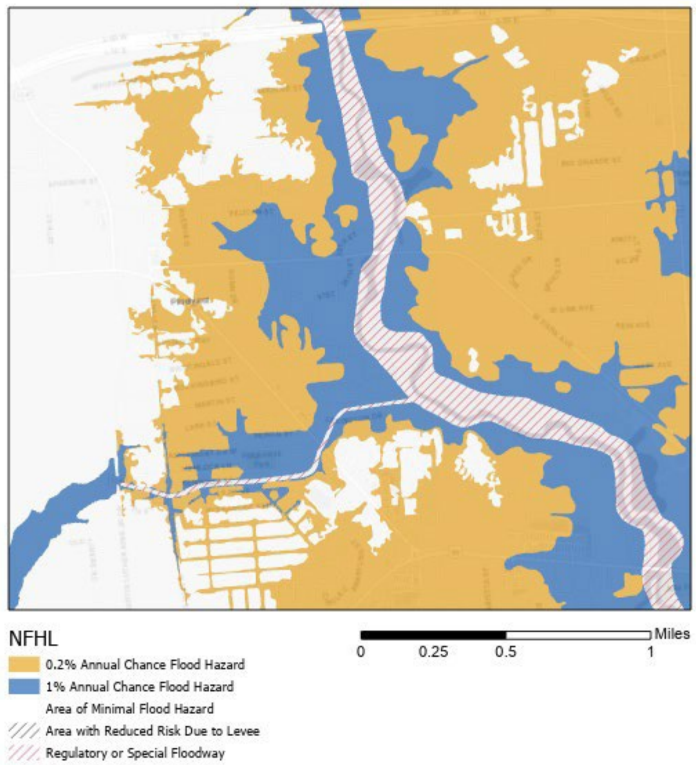

Figure 20. FEMA NFHL (FEMA, 2021), Port Arthur, TX

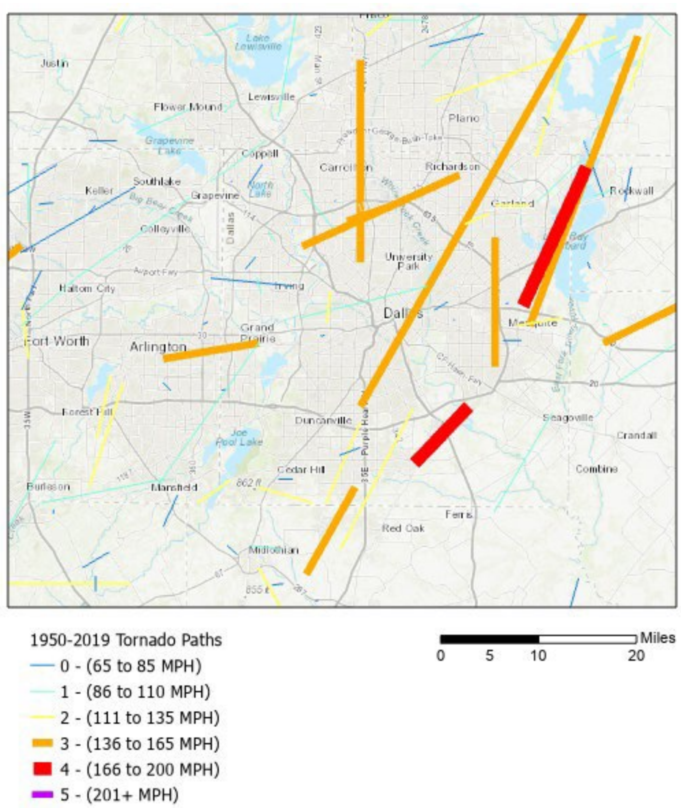

Figure 21. Tornado Track through Dallas, TX, October 20th, 2019, data from NOAA (NOAA, 2022)

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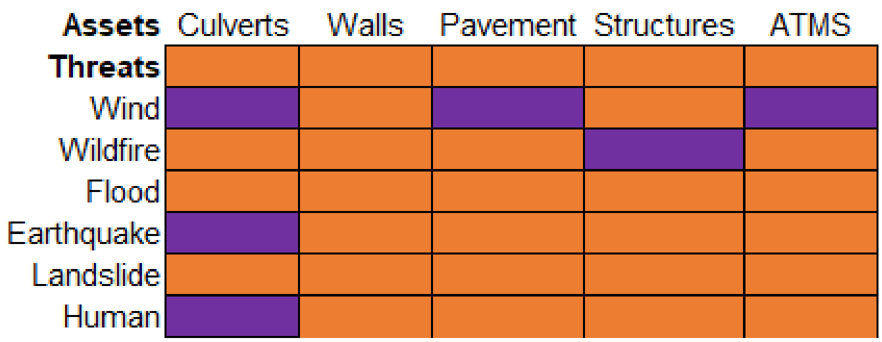
An example of a threat-asset pair matrix is presented in Table 15. Threats are listed in the left-hand column, and assets are listed in the top row. Relevant threat-asset pairs are symbolized in orange. The color purple indicates no threat (Institute for Trade and Transportation Studies, 2020).

Table 15. Example Threat-Asset Matrix for Transportation



5.2.2 Data Sources to Support Threat Modeling

Spatial data in the form of digital maps superimposed over study area boundaries and asset inventory help identify the hazards that are relevant to a given study area and identify assets at risk. There is currently a plethora of publicly available spatial data that can be downloaded as a shapefile, KMZ file, GeoJSON, spatial database, or accessed online through a REST service. Key national sources include the U.S. Geological Survey, NOAA, U.S. Department of Homeland Security, and FEMA, among others. In addition, many agencies of transportation have invested in developing the spatial data inventories curated by state, county, and local agencies.

Table 16 lists examples of spatial data for modeling hazards, extreme weather, and climate change – all free and from public sources.

Table 16. Examples of Special Data for Hazard Modeling

Hazard	Data	Description	Source
Flood	DFIRM	Digital flood insurance rate map with boundaries for 100/500-year floodplain (vector polygon)	FEMA
	Peak Flows	Watershed basin characteristics and peak flow for 1.25 to 500-year events for ungauged sites, downloadable as vector	USGS StreamStats

Hazard	Data	Description	Source
		polygon, CSV, or PDF report.	
	Stream Network	ESRI Geodatabase with polyline vector feature classes	USGS NHD Plus
	NOAA Atlas 14	Rainfall intensity and accumulation by return period in table form	NOAA
	Real-Time Weather Data	Current and forecast weather data	OpenWeather
Earthquake	Shake Maps	PGA, PGV, spectral acceleration 1-second and 0.3 second periods (HAZUS-ready shapefiles)	USGS Earthquake hazards Program
	Quaternary Faults	Quaternary fault and fold database for the US, download as KML or polyline shapefile	USGS Faults
	Historic Epicenters	Included are earthquakes located in the United States and some that occurred in adjacent portions of Canada and Mexico. The main sources for the data are Seismicity of the United States, 1568-1989, and the Preliminary Determination of Epicenters for 1990 to August 2009.	Homeland Infrastructure Foundation-Level Data
	Real-time feed (GeoJSON)	Earthquake event data is updated every minute. Can access Significant Earthquakes, M4.5+, etc.)	USGS Earthquake Feed
Landslide	US Landslide Inventory	Mostly polygon vector representations of landslide extent points where extent has not been mapped.	USGS

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Hazard	Data	Description	Source
	Susceptibility	This map layer, utilizing data from the U.S. Geological Survey, delineates areas in the conterminous U.S. where large numbers of landslides have occurred and areas that are susceptible to landslides	USGS Landslide Susceptibility
	Frequency-Precipitation	Estimate the annual frequency of landslides triggered by precipitations.	Global Risk Data Platform
	Frequency Earthquake	Estimate the annual frequency of landslides triggered by earthquakes.	Global Risk Data Platform
	Elevation/Slope	30 m to 1 m cell resolution digital elevation grids, Lidar	USGS – The National Map
	Soil	Various soil characteristics, depth to water, depth to bedrock (Microsoft access database)	USDA Web Soil Survey
Post Fire Debris Flow	US Landslide Inventory	Mostly polygon vector representations of landslide extent points where extent has not been mapped.	USGS
Wildfire	Fire Perimeters	US Historical fire perimeters from 2000 to 2018. Perimeters were originally downloaded from the Geospatial Multi-Agency Coordination (GeoMAC) by USGS.	ArcGIS Online
	Burn Probability	The Mean Fire Return Interval (MFRI) layer quantifies the average period between fires under	Landfire

Hazard	Data	Description	Source
		the presumed historical fire regime.	
	Debris Flow After Fire	Debris flow runout zone (vector polygon) with estimated debris volumes and probabilities	USGS Post Fire Debris Flow Assessments
Tornado	Historical tornado tracks (1950 – 2019)	Tornado tracks are available as paths or initial points.	NOAA Storm Prediction Center (SPC)
Hail	Historical hailstorms (1950 – 2019)	Hailstorms are available as paths or points.	NOAA SPC
Wind	Historical strong winds (1950 – 2019)	Windstorms are available as paths or points.	NOAA SPC
Hurricane	Advisory wind field and forecast wind radii, wind speed probabilities	National Hurricane center data is available as shapefiles and KMZ.	National Hurricane Center
Storm Surge	Hazard Map	Gridded storm surge maps were developed using SLOSH Storm Surge modeling. Latest version – is 2018.	NOAA
Sea Level Rise	Depth grid	1-6 ft sea level rise inundation extent. Gridded spatial data downloadable by state. Note: the files are large.	NOAA
Climate Change	Downscaled CMIP5	Download LOCA CMIP5 data for multiple time periods and up to 20 Global Climate Models. This data can be processed for transportation usage with	Bureau of Land Reclamation

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Hazard	Data	Description	Source
		the FHWA online CMIP5 tool.	

It is important to note that hazard and climate/environmental data may also be available in tabular formats, such as Excel spreadsheets or delimited text files. Table 17 gives three examples.

Table 17. Example Tabular Data Sources

Hazard	Data	Description	Source
Climate Change	CMIP5 downscaled climate data	Downloadable in CSV or netCDF Format.	Bureau of Land Reclamation
Climate Extremes	"The U.S. Climate Extremes Index (CEI) is the arithmetic average of the following five or six indicators of the percentage of the conterminous U.S."	Downloadable as an Excel spreadsheet.	NOAA
Hydrological	Peak Streamflow for gauged streams.	Downloadable as XML file or tab-delimited spreadsheet	USGS

In addition to the natural hazard and climate-related data sources discussed above, the data sources described in Table 18 and Table 19 may assist in modeling terrorism and cyber-attacks, respectively. Texas A&M University library hosts a website with links to data sources on terrorism (see Table 18).

Table 18. Source of Data on Terrorism

Data Source	Comments
Iterate Dataset (Duke University Libraries, 2018)	"A textual chronology of international terrorism which employs inter alia an exhaustive search of major media including information obtained from interviews with government officials, scholars, and former hostages/others involved in international terrorist incidents."

Data Source	Comments
Global Terrorism Database (University of Maryland, 2020)	"Information on terrorist events around the world from 1970 through 2013 includes systematic data on domestic and international terrorist incidents that have occurred during this time period and now includes more than 125,000 cases."
Suicide Attack Database (1974-2016) (Princeton University, 2016)	"Data on all suicide attacks from 1982 through November 2014 including information about the location of attacks, the target type, the weapon used, and systematic information on the demographic and general biographical characteristics of suicide attackers." Currently offline.
Terrorism and Extremist Violence in the United States (TEVUS) database (LaFree, et al., 2019)	"Integrates existing and new open-source data sets to facilitate more robust and sophisticated analyses of violent extremists' behaviors, operations, and activities within the United States."
American Terrorism Study (1980-2002) (Smith & Damphousse, 2007)	"Dataset that includes information on nearly 500 terrorists from about 60 terrorist groups indicted for more than 6,700 Federal criminal counts."
RAND Database of Worldwide Terrorism Incidents (RAND Corporation, 2018)	"Compilation of data from 1968 through 2009 With over 40,000 incidents of terrorism coded and detailed."

Souppaya and Scarfone discuss modeling cyber threats in detail (Souppaya & Scarfone, 2016), while Hug et al. researched threats to intelligent transportation systems (ITS) (Huq, Vosseler, & Swimmer, 2017). Table 19 lists sources of information relevant to cyber threats.

Table 19. Data Sources for Cyber Security Threat Analysis

Data Source	Comments
Center for Strategic & International Studies Significant Cyber incidents (CSIS (Center for Strategic & International Studies), 2021)	"This timeline records significant cyber incidents since 2006. We focus on cyber-attacks on government agencies, defense and high-tech companies, or economic crimes with losses of more than a million dollars."

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Data Source	Comments
Cyber Operations Tracker (Council on Foreign Relations, 2021)	"The Digital and Cyberspace Policy program's cyber operations tracker is a database of the publicly known state-sponsored incidents since 2005."
VIZSEC (VizSec Organization, n.d.)	VizSec is an independent organization devoted to researching data mining and visualization for computer security. Vizsec's data page lists many links to data sets.
National Vulnerability Database (National Institute of Standards and Technology (NIST), n.d.)	"The NVD is the U.S. government repository of standards-based vulnerability management data represented using the Security Content Automation Protocol (SCAP). This data enables the automation of vulnerability management, security measurement, and compliance. The NVD includes databases of security checklist references, security-related software flaws, misconfigurations, product names, and impact metrics."

5.2.3 Types of Threat Modeling

This section will cover approaches to threat modeling. Threat modeling encompasses the following aspects: threat extent (spatial boundaries), frequency (likelihood of occurrence), and intensity (magnitude).

Methodologies for estimating extent depends on the type of threat, i.e., geotechnical, seismic, or hydrological. Free-ware tools, such as the *Flow-R* and *Q-Proto*, a QGIS plugin, and commercial tools such as RocScience's *Rockfall*, are software solutions for modeling geotechnical events, such as landslides, debris flows, and rockfall. Typical inputs include digital elevation data, slope angle, ground cover, debris volume, location of the debris source, etc. Figure 22 demonstrates the use of Flow-R to model the runout zone of a rock avalanche (Oppikoger, Hermanns, Sandoy, & Bohme, 2016). The relative probability of propagation is symbolized with a yellow-to-red color ramp.

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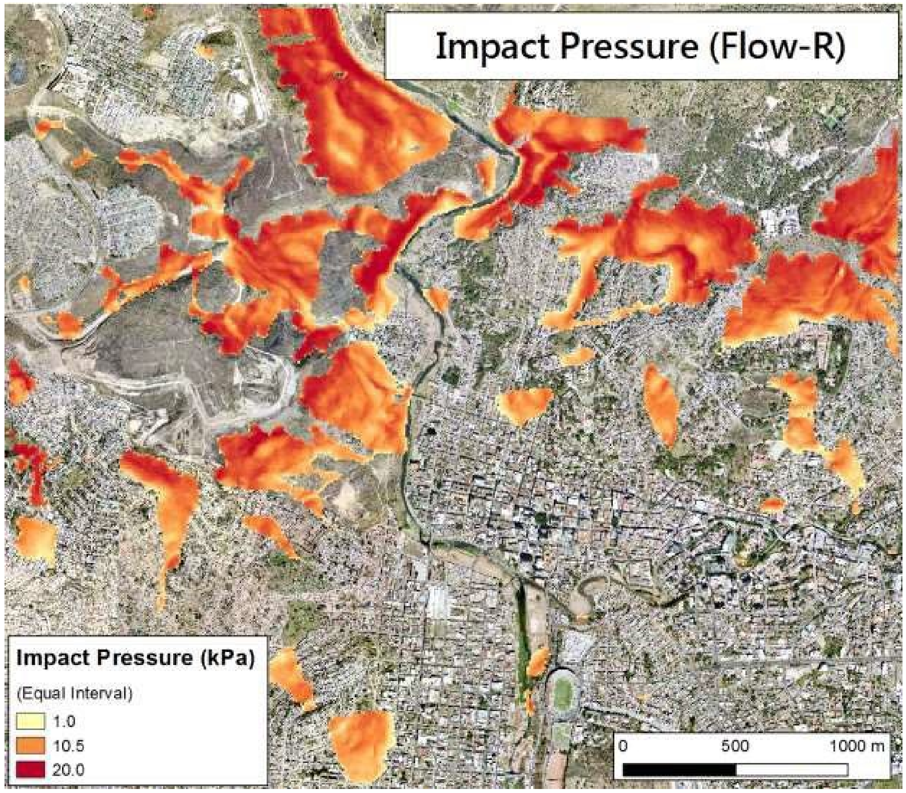

Figure 22. Runout Modeling of a Potential Rock Avalanche using Flow-R Software

The extent of a seismic threat is determined by attenuation curves. Attenuation curves calculate the shaking parameter (e.g., peak ground acceleration, peak ground velocity, etc.) in terms of distance from the earthquake source, i.e., ground shaking is attenuated with distance from the source (FEMA, 2020). Shake maps (maps of ground shaking) reveal both the extent and intensity of a seismic event. For example, the shake map for the 1971 San Fernando earthquake (see Figure 23 (USGS, 1971)) symbolizes the region of greatest intensity in red, closest to the earthquake epicenter, while the intensity diminishes with distance from the epicenter, symbolized with a color shift from orange, to yellow, to green, etc. It is important to note that shake maps illustrate both extent and intensity.

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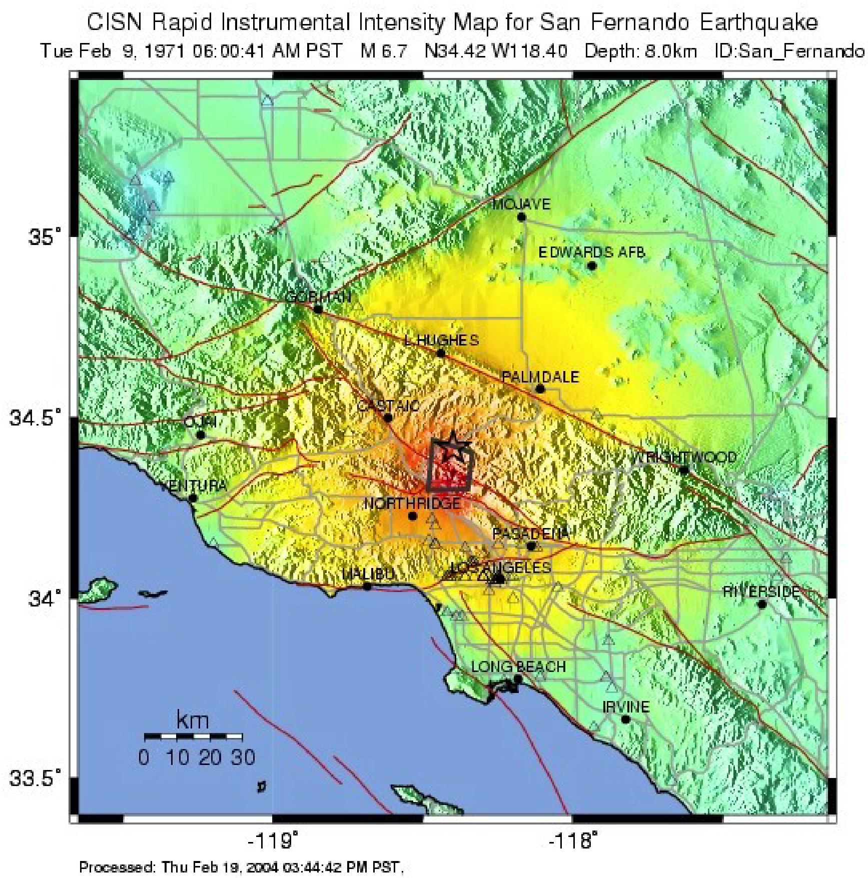

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 23. USGS Shake Map for San Fernando Earthquake, February 9, 1971 (USGS, 1971)

Modeling the extent of hydrological events, or floodplain modeling, requires hydrological and hydraulic modeling". FEMA (FEMA, 2017) defines a Hydrologic and Hydraulic (H&H) study as "the study of the movement of water, including the volume and rate of flow as it moves through a watershed, basin, channel, or man-made structure." Hydrologic modeling determines how much water from a precipitation event will become runoff and, thus, available to flood an area, while hydraulic modeling shows where the water travels to. GIS software is used to develop digital flood maps, incorporating such inputs as terrain models, elevation data, and imagery. USACE's HEC-RAS software (USACE) is widely used (see Figure 24).

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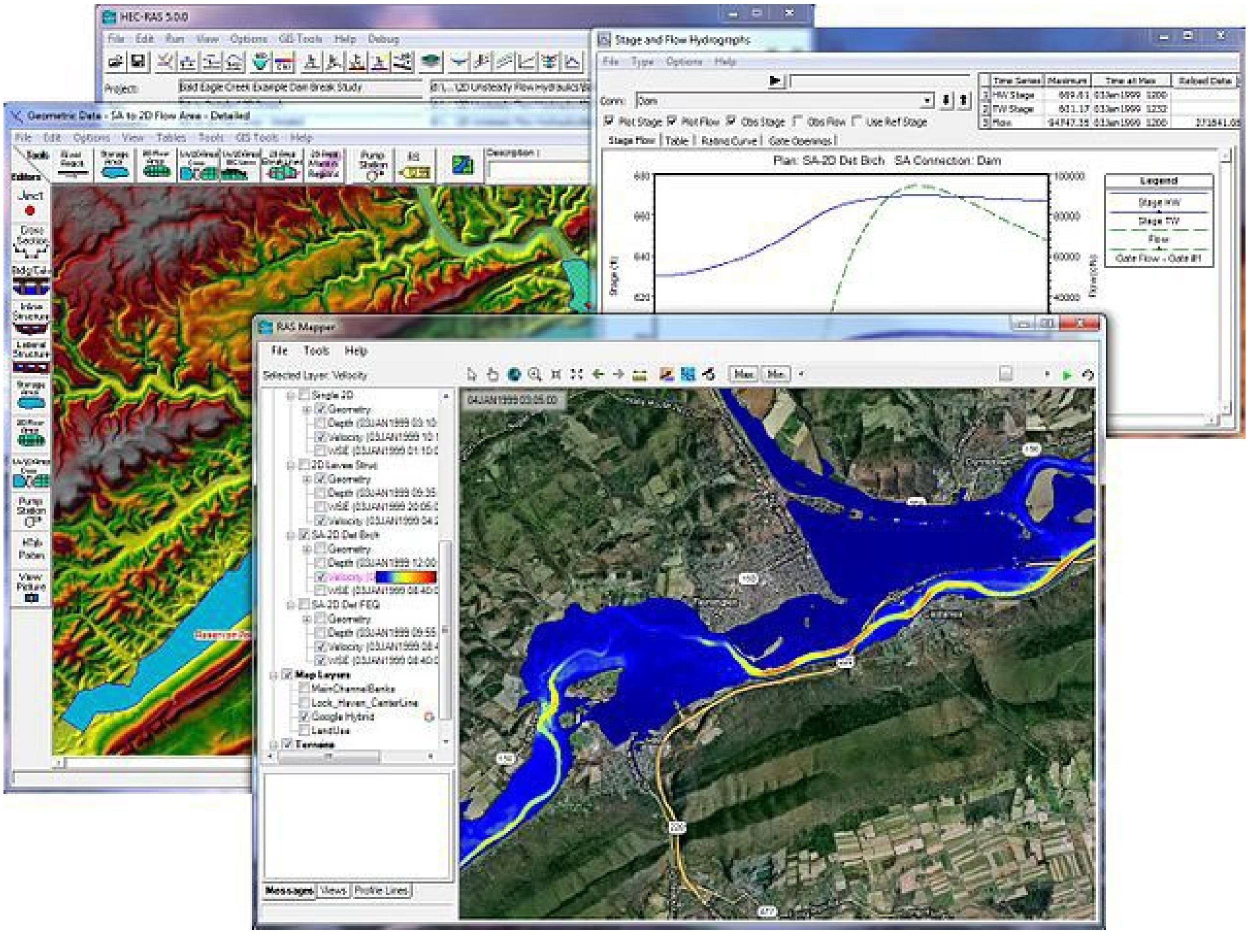

Figure 24. USACE HEC-RAS H&H Modeling Software, from Wikimedia Commons

There are deterministic and probabilistic approaches for accomplishing both to describe intensity and frequency, i.e., frequency-magnitude relationships. Deterministic models are entirely determined by their parameter values and initial conditions. A deterministic model produces a single output and is thus suitable for modeling a single event. In contrast, a probabilistic model outputs a distribution of multiple values after running a simulation involving hundreds or even thousands of trials. Probabilistic modeling includes Monte Carlo simulation and graphical models, such as Bayesian Belief Networks and Markov Networks. Monte Carlo simulations, Bayesian Networks, and Markov Chains are statistical models that incorporate probability distributions to capture the uncertainty associated with the parameters used (Bratvold & Begg, 2010).

Deterministic approaches include frequentism, power laws, and extreme value probability distributions. The frequentist approach calculates the number of physical events that occur per interval of time. Frequency is usually expressed as an exceedance probability, defined as the probability that an event with a certain magnitude will occur within a given year. For example, if a magnitude 6 earthquake occurs once every 500

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years, the frequency is 1/500 or 0.02 %. If the return period of an event is known, such as a "100-year flood", then the frequency is simply one over the return period or 1%. With an inventory of historical data that includes the magnitude of each event, it is possible to use an extreme value distribution, such as Gumbel or Poisson to calculate the frequency for each event magnitude. Here is an example of how to calculate flood frequency.

Frequency-magnitude analysis for flood events involves relating the magnitude of a flood to its frequency of occurrence through a probability distribution. Flood magnitude is usually measured in terms of discharge. Hydrologists derive flood frequency from annual peak streamflow values. The US Geological Survey's National Water Information System web interface provides access to peak streamflow data (USGS, n.d.). Probabilistic methods to derive estimates of frequencies have also been applied to rockfall (Corona, et al., 2017), debris flows (Malet & Remaitre, 2015), and snow avalanches (Perona, Mischer, & Porporato, 2009), etc.

Interest in modeling interactive and cascading threats has grown in recent years (Pescaroli & Alexander, 2018; Girgin, Necci, & Krausmann, 2019). Some risk assessment frameworks and methodologies emphasize the importance of including threat interactions in risk models, especially in cases where such interactions may exacerbate the overall risk. Generally, the study of interacting threats involves identifying hazards that trigger other hazards. Cascading risks can involve interactive threats and overlapping and compounding socioeconomic consequences. For example, the disaster that struck Japan on March 11, 2011, was an earthquake that triggered a tsunami that resulted in a nuclear meltdown at the Fukushima power plant, causing power outages, contamination, and evacuations.

Some studies have identified four types of threat interactions (Gill & Malamud, 2014).

- Interactions where a hazard is triggered; for example, an earthquake triggers a landslide.
- Interactions where the hazard probability is increased; for example, wildfire increases the probability of a debris flow
- Interactions where the probability of a hazard is decreased; for example, a heavy rainstorm decreases the probability of a wildfire
- Events involving the spatial and temporal coincidence of natural hazards; for example, a volcano erupts, followed by a typhoon, causes lahars on the volcano's slopes.

Examples of these interactions include (Gill & Malamud, 2014):

- Japan (1972): Landslide and Tsunami

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- Alaska (1964): Earthquake and Tsunami
- Philippines (1991): Volcano eruption and Earthquake/Sulfur expulsion
- Guatemala (2010): Tropical rainstorms and Mass movements

Table 20 presents a matrix showing the interaction of avalanches, debris flows, rockfalls, landslides, floods, heavy rainfall, and earthquakes (Kappes, Keiler, & Glade, 2010).

Table 20. Interactive Hazards, adapted from (Kappes, Keiler, & Glade, 2010)

	Avalanche	Debris Flow	Rockfall	Landslide	Flood
Avalanches					X
Debris Flow					X
Rockfall					X
Landslides					X
Floods				X	
Rainfall	X	X		X	X
Earthquake	X		X	X	

5.3 Estimating Vulnerability of Assets from Relevant Threats or Hazards

Another important step for performing risk and resilience analysis is estimating vulnerability. This section discusses definitions of vulnerability and the different factors and tools used to assess vulnerability.

Similarly, to the definitions of Risk and Resilience, definitions for vulnerability varies depending on sector that is used.

In general, there are many definitions of vulnerability, but several common themes emerge a degree of loss, an adverse effect, a susceptibility to damage, a weakness, and ability to cope, or a measure of uncertainty that consequences will occur if a threat occurs (see Table 21).

Table 21. Definitions of Vulnerability

Definition	Sector	Source
"The conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards."		UN/ISDR (2004) (UN/ISDR, 2004)
"Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse		IPCC (2007) (IPCC, 2007)

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Definition	Sector	Source
effects of climate change, including climate variability and extremes."		
"Vulnerability has been defined as the degree to which a system, or part of it, may react adversely during the occurrence of a hazardous event. This concept of vulnerability implies a measure of risk associated with the physical, social and economic aspects and implications resulting from the system's ability to cope with the resulting event."	Economics	Proag (2014) (Proag, 2014)
"Vulnerability analysis consists of estimating the conditional likelihood a threat will have on consequences …, given that the threat occurs."	Engineering	ASCE (2009) (ASME, 2009)
"Vulnerability is defined as ''the degree to which the system is susceptible to and is unable to cope with adverse effects of change."	Water	Adger (2006) (Adger, 2006), Anandhi et al (2018) (Anandhi & Kannan, 2018)
The vulnerability of each target depends on its capacity to resist various hazard values generated by surrounding sources. Vulnerability represents the potential weakness of whole targets to the hazard generated from each source."	Construction	Abunemeh et al (2017) ((Abunemeh, El meouche, Hijaze, Mebarki, & Shahrour, 2017)
A weakness in system security procedures, design, implementation, internal controls, etc., that could be accidentally triggered or intentionally exploited and result in a violation of the system's security policy."	IT	CRSC (2020) (Computer Security Resource Center Information Technology

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Definition	Sector	Source
		Laboratory, n.d.)

Definitions of vulnerability within the transportation sector consider system performance. In her seminal paper, Berdica (2002) (Berdica, 2002) defined vulnerability as "a susceptibility to incidents that can result in considerable reductions in road network serviceability." Similarly, Mattson and Jenelius (2015) described transport system vulnerability as "society's risk of transport system disruptions and degradations." Gao et. al (2019) (Gao, et al., 2019) asserted that vulnerability stems from the factors that can contribute to the reduction of a network's maximum service level and, further, that topology determines performance.

In addition to the multiple definitions of vulnerability, there are also multiple methodologies that estimate the vulnerabilities of the transportation network or assets. Vulnerability assessments may be based on stakeholder input, indicator-based desk review approaches, or engineering-based analysis. The use of each type of assessment will vary depending on the individual agency's needs and capabilities.

FHWA presents an overview of these types of vulnerability assessments in their Vulnerability Assessment and Adaptation Framework (VAAF) report (Filosa, Plovnick, Miller, & Pickrell, 2017). Based on this methodology, a spreadsheet tool named the Vulnerability Assessment Tool (VAST) was developed to help users to estimate vulnerabilities using a scoring process.

As mentioned in previous sections, transportation agencies widely use FHWA VAAF to assess their system's vulnerability to climate change and extreme weather events (Filosa, Plovnick, Miller, & Pickrell, 2017). Figure 25. FHWA Vulnerability Assessment and Adaptation Framework (VAAF) (Filosa, Plovnick, Miller, & Pickrell, 2017)Figure 25 shows the different steps of this framework. The framework defines vulnerability as a function of exposure, sensitivity, and adaptive capacity.

To determine exposure of an asset or system to a particular threat, the use of hazard maps should be implemented. Overlaying of threat maps over the asset/system should help to identify if the asset or system might be located or exposed to such threat – e.g., a FEMA Digital Flood Insurance Map (DFIRM), landslide inventory, or earthquake shake map. **Sensitivity** is assessed by weighing the severity of a threat against the design characteristics and condition state of the exposed asset/system. Examples of **adaptive capacity** include detour length, route redundancy, the number of snowplows on hand, and the response time of maintenance crews.

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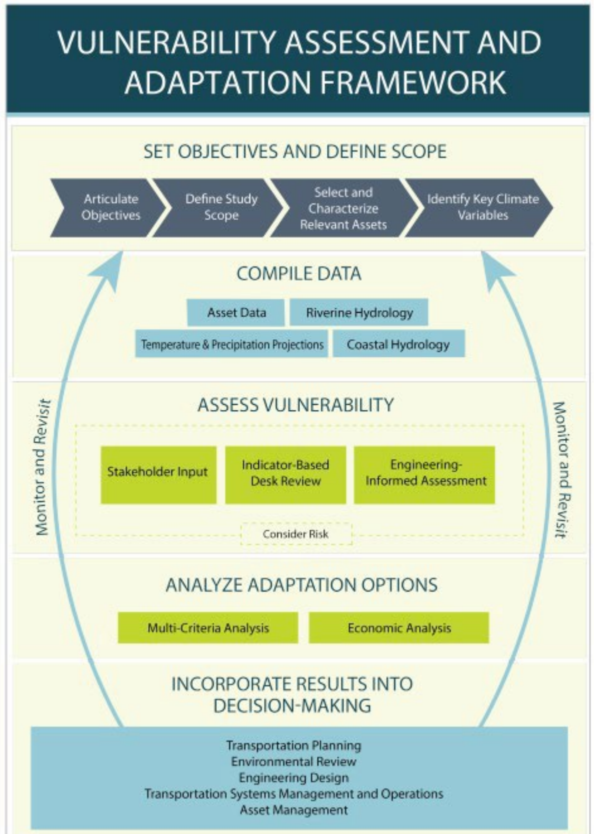

Figure 25. FHWA Vulnerability Assessment and Adaptation Framework (VAAF) (Filosa, Plovnick, Miller, & Pickrell, 2017)

The FHWA sponsored 19 resilience pilots pilot projects, between 2013-and 2015, for state DOTs and Metropolitan Planning Organizations (MPOs) to assess the vulnerability of their transportation systems. Many of these pilot projects implemented FHWA VAAF to perform their vulnerability assessments. Some of these projects include (Filosa, Plovnick, Miller, & Pickrell, 2017):

- Arizona DOT conducted a vulnerability assessment of the state highway system to extreme weather, including higher temperatures, drought, and intense storms,
- Connecticut DOT assessed their system vulnerability, including bridges and culverts to flooding.
- Maine DOT conducted vulnerability assessments of sea-level rise and storm surge in six coastal towns to develop depth damage functions and adaptation design options for individual sites.

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- Capital Area Metropolitan Planning Organization (CAMPO) and the City of Austin conducted vulnerability and risk assessments from flooding, drought, extreme heat, wildfire, and ice to nine critical assets

Currently, FHWA is also sponsoring another 11 pilot projects to estimate resilience and durability to extreme weather, including the use of available tools for vulnerability and risk assessment (FHWA, n.d.).

In addition to vulnerabilities generated based on scoring a series of paraments, vulnerabilities also measure a degree of loss to an exposed element-at-risk and are expressed on a scale from 0 (no damage) to 1 (total damage). (Argyroudis, Mitoulis, Kaynia, & Winter, 2018) stated that vulnerability of transportation infrastructure can be evaluated in terms of repair costs, life-safety impacts, or degradation of performance and is related to the asset's susceptibility to damage for a given measure of hazard intensity (e.g., force, seismic loading, ground deformation, etc.). Note that vulnerability correlates the characteristics of the element-at-risk to the hazard intensity.

This relationship is analogous to the concept of sensitivity found in VAAF and the applied sciences and is expressed in terms of a damage or fragility curve.

Damage states are usually based on the time it takes to restore transportation assets to their original capacity and, in some cases, on the asset's replacement or repair cost. An example of damage states for roads and railways subjected to vertical ground displacement is presented in Table 22 (Argyroudis, Mitoulis, Kaynia, & Winter, 2018).

Table 22. Damage States for Highways and Railways Subjected Vertical Ground Displacement

		Permanent Vertical Ground Displacement (m)			**Serviceability**
Typology	**Damage State**	Min	Max	Mean	
Highways	Minor	0.02	0.08	0.05	Open, reduced speeds, or partially closed during repair.
	Moderate	0.08	0.22	0.15	Closed or partially closed during repair works
	Extensive/Complete	0.33	0.58	0.40	Closed during repair works
Railways	Minor	0.01	0.05	0.03	Open, reduced speeds.

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	Moderate	0.05	0.10	0.08	Closed during repair works
	Extensive/Complete	0.10	0.30	0.20	Closed during reconstruction works

Another example of damage state/factor includes fragility curves. Figure 26 illustrates example damage or fragility curve for roadways subjected to inundation. The damage factor is measured against flood depth in meters.

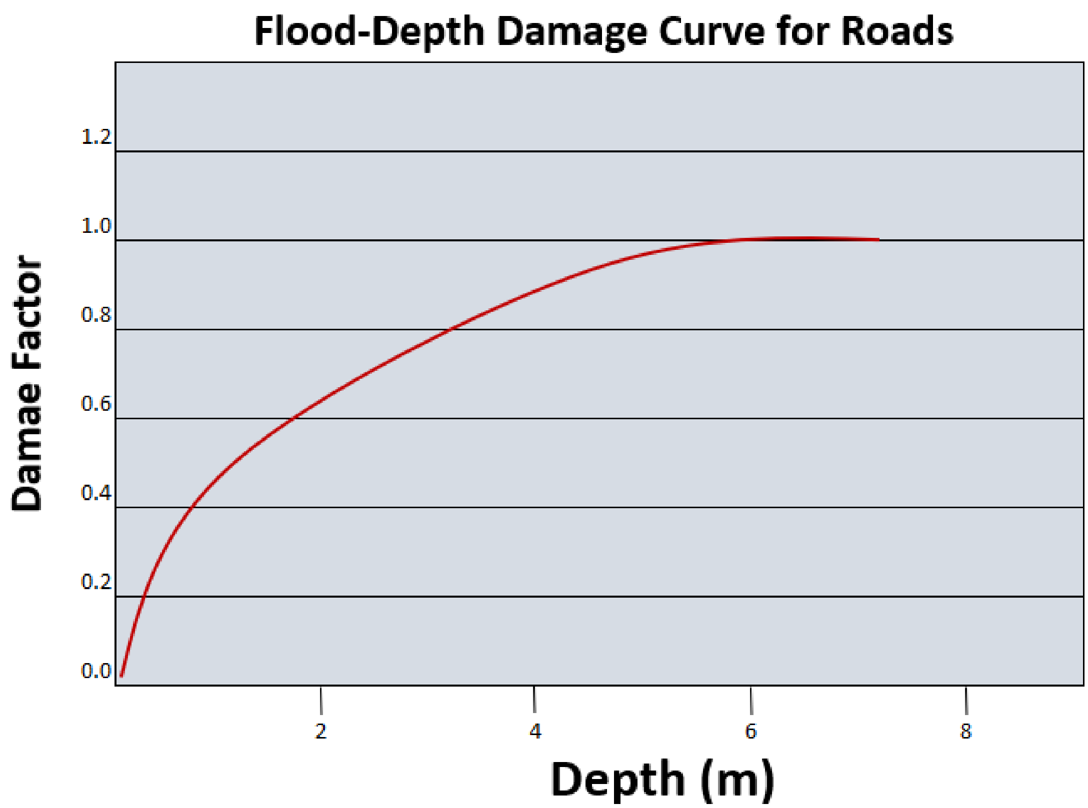

Figure 26. Example Flood-Depth Damage Curve for Roads

This type of fragility or damage curve is more advanced in specific fields than others. The fields of seismology and flood science are some of the most advanced fields, while the fields of geotechnical hazards (i.e., landslide, debris flow, subsidence, etc.) are less developed. However, some attempts have been made to quantify roadway vulnerability to landslides. For example, (Winter, et al., 2014) developed damage curves for debris flow and three damage states based on responses to surveys sent to experts from around the world (see) where the degree of damage was correlated with debris flow volume (m^3) (see Figure 27).

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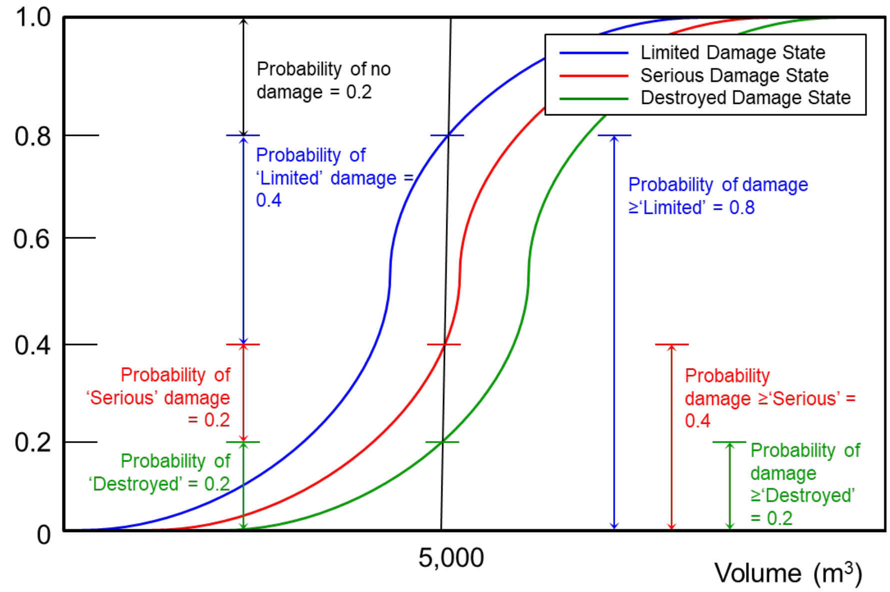

Figure 27. Damage Curve for Debris Flow and Roadway (Winter, et al., 2014)

Other examples of vulnerabilities based on damage factors of probabilities are developed by engineering judgment and historical performance and damage records. Examples of these vulnerability curves or tables can be found in the Colorado DOT Risk and Resilience Analysis Procedure (AEM Corporation, 2020). These vulnerability tables were developed by subject matter experts of each field, including hydraulic, rockfall, etc. through a series of workshops to validate the models and variables used. Table 23 presents one of the vulnerability tables developed for CDOT's Risk and Resilience Procedure, where vulnerabilities range from 0-to 1.

Table 23. CDOT's Risk and Resilience Procedure Roadway flood vulnerabilities (CDOT, n.d.)

Flood Event Magnitude	Terrain	Embankment Erodibility Potential				
		Very Low	Low	Moderate	High	Very High
100-yr	Level	0.22	0.23	0.25	0.31	0.33
	Rolling	0.26	0.28	0.30	0.36	0.39
	Mountainous	0.35	0.37	0.40	0.48	0.52
500-yr	Level	0.55	0.59	0.63	0.77	0.83
	Rolling	0.66	0.70	0.75	0.91	0.99
	Mountainous	0.88	0.93	0.99	0.99	0.99

As shown in this section, vulnerability assessments may be qualitative or quantitative, however, most vulnerability assessments are based on exposure to threats and how well the asset will perform under such exposure.

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5.4 Types of Consequences from Identified Threats

Along with threats and vulnerability assessment, consequence estimation from applicable threats is a key factor in risk and resilience analysis.

Different consequences can be estimated and included in risk and resilience analysis.

RAMCAP Plus™ (ASME, 2009) defines consequences as "The outcome of an event occurrence, including immediate, short, and long-term, direct and indirect losses and effects. Loss may include human fatalities and injuries, monetary and economic damages, and environmental impact, which can generally be estimated in quantitative terms." Additionally, consequences can be subdivided into owner, user, operational, and safety. This section addresses the consequences component of risk analysis.

Asset loss is a first-order, direct consequence of an adverse event. Sometimes referred to as the owner's financial loss (ASME, 2009), asset loss can be expressed as a percentage of repair or replacement costs and cleanup costs when applicable. The degree of loss can be quantified through the application of a damage function (fragility curve, vulnerability curve, susceptibility curve, etc.) derived empirically (e.g., percent damage suffered by a building versus flood elevation) or synthetically, i.e., through expert opinion (Kreibich & Bubeck, 2013; Meyer, Becker, Markantonis, & Schwarze, 2012). The percentage of damage, estimated by the damage function, can be multiplied by the replacement cost or repair cost to quantify the asset loss. Alternatively, total estimates of loss can be correlated with some measure of hazard intensity (flood depth, peak ground acceleration, cubic meters of debris, etc.).

Loss of functionality is also a direct consequence. Sometimes referred to as user consequences, loss of functionality impacts users due to the additional costs incurred by travel delays (lost wages and other vehicle operating costs), additional travel distance, or drive time. The FHWA HYRISK procedure for evaluating the economic losses due to bridge pier scour includes a calculation for user consequences based on traffic volume, number of days of delay, average wages, and other factors (Stein & Sedmera, 2006). The CDOT Risk and Resilience Procedure's manual incorporates a modified version of the equation from HYRISK to calculate costs incurred from partial closure (work zone user costs) (CDOT, n.d.).

Other approaches to evaluating loss of functionality include travel demand modeling, restoration curves, and multi-criteria index models. Travel demand models, macroscopic traffic assignment models, and traffic simulation models have been used to estimate system-level consequences from asset loss or disruptions (due to temporary loss of function). Disruptions have been modeled by disabling links in these networks and disallowing assigning trips to the disrupted links or constraining their capacity. The use of a combined travel demand model incorporating trip generation, destination,

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mode, and route choices was proposed to assess the long-term equilibrium effects of the closure of one or more links (Chen, Yang, Kongsomsaksakul, & Lee). The consequences are calculated as the decrease of a utility-based accessibility measure.

Network performance related to disruptions has been researched over the years to consider concepts such as vulnerability, reliability, robustness, accessibility, and resilience. This led to the development of associated measures and indices, including the Link Performance Index for Resilience (LPIR) (Calvert & Snelder), which evaluates the level of resilience of individual highway sections in relation to a wider network used to detect sections with a low resiliency ranking and to analyze the underlying characteristics that make them so. A different index known as the Network Robustness Index was used to identify important links in a highway network. This index for a network link is defined as the increase in user equilibrium travel time that is incurred when the link is closed, which was subsequently modified to allow a less-than-total disruption and allow for comparisons between different transport networks to calculate system-level robustness (Sullivan, Novak, Aultman-Hall, & Scott).

In addition to asset loss, damage curves can be applied to assessing the loss of functionality from disruptions. A relationship between depth of standing water and vehicle speed was developed by fitting a curve to video analysis supplemented by empirical data and literature (Pregnolato, Ford, M.Wilkinson, & J.Dawson). This work enabled incorporating the water depth and vehicle speed function into existing transportation models to develop better estimates of flood induced delays. The sensitivity of assets and their vulnerability to withstand a range of disruptions has been modeled using fragility and restoration models, especially for highway bridges. David Turner developed fragility curves for eight existing bridges in Colorado, considering a single damage state corresponding to structural failure of the bridge super-structure due to riverine flood-induced hydrodynamic lift forces (Turner, 2015). A comprehensive review of fragility and restoration models was performed for typical bridge classes for application in multi-hazard risk and resilience analyses of transportation networks in the US (Chen, Ioannis, Jamie, & Barbosa).

Similarly, Mattson and Jenelius compiled an extensive review of the state-of-the-art for modeling the consequences of disruption to the transportation system (Mattsson & Jenelius).

Jan Husdal proposed a project evaluation process using a multi-criteria analysis for non-monetary and monetary impacts (Husdal). The process employs a weighted multi-criteria decision approach involving the assessment of link closures or disruptions which are assessed by the severity of the impact, allowing for the assessment of individual effects or impacts. The evaluation criteria and the incremental values shown in Table 24 are illustrative.

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Table 24. Disruption Evaluation Criteria (Husdal)

Evaluation Category / Impact	Negligible (1)	Low (2)	Some (3)	Serious (4)	Severe (5)
(A) AADT	≤ 500	≤ 1000	≤ 2000	≤ 5000	> 10000
(B) Closure/Waiting Time - light vehicles (Wltv)	Wtlv ≤ 1h	1h < Wtlv ≤ 3h	3h < Wtlv ≤ 6h	6h < Wtlv ≤ 1d	Wtlv > 1d
(C) Closure/Waiting Time - heavy vehicles (Wthv)	Wthv ≤ 1h	1h < Wthv ≤ 3h	3h < Wthv ≤ 6h	6h < Wthv ≤ 1d	Wthv > 1d
(D) Perishable goods, loss of value	% monetary value marginal value	% monetary value marginal value	% monetary value marginal value	% monetary value marginal value	% monetary value marginal value
(E) Business loss of profit	% monetary value marginal value	% monetary value marginal value	% monetary value marginal value	% monetary value marginal value	% monetary value marginal value
(F) Reconstruction time (Rt)	< 1wk	1wk <Rt ≤1mo	1mo <Rt ≤3mo	3mo <Rt ≤6mo	> 6 mo

An example of a software application that can model both asset loss and loss of functionality is FEMA's HAZUS-MH add-in to ArcGIS Desktop. For example, the HAZUS-MH flood model (Multi-hazard Loss Estimation Methodology) estimates damage to transportation lifeline systems based on the vulnerabilities of the various components to inundation, scour, erosion, debris impact, and hydraulic loading. The transportation lifeline lifecycle components selected for fragility modeling are primarily bridges. Impacts on system functionality, component costs, and recovery time from damage are also considered.

A commercially available tool for modeling the economic consequences of disruptions to the transportation system is REMI's *TranSight* which includes travel demand modeling. In the Federal Highway adaptation pilots conducted by Hillsborough MPO and Resilience Tampa Bay (RTBT), the Tampa Bay Regional Planning Council (TBRPC) analyzed the economic impacts of transportation system disruptions from six representative projects and two extreme weather scenarios for internal flooding and hurricane events using REMI *TranSight* (Version 4.0). Using outputs generated from the Tampa Bay Regional Planning Model (TBRPM) for 2045, TBRPC modeled the potential impacts of each event disrupting selected transportation links for one week. Results were reported using Gross Regional Product (GRP) and personal income (or wages) as indicators.

Modeling safety (societal) consequences, i.e., losses due to fatalities or injuries, involves knowing the statistical value of human life and the probability of exposure. Risk curves

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for fatalities are called FN curves. FN curves display the probability of having N or more fatalities per year as a function of N. FN-Curves can be based on historical data, probabilistic modeling, or expert opinion.

The U.S. Department of Transportation used Census of Fatal Occupational Injuries (CFOI) data and a synthesis of multiple studies to estimate the statistical value of human life. In 2015 the estimate was $9.4 million (Moran & Monje, 2016). The estimate is a fixed value and is not adjusted for age, gender, economic status, or other demographic characteristics (Bosworth, Hunter, & Kibria, 2017).

Calculating the safety risk to a drive involves estimating the likelihood of exposure. Wylie expressed exposure to risk as a function of the road cut length, traffic count, and vehicle speed (see Equation 4) (Wylie, 2015).

$$Exposure\ risk = LN/(Vx86{,}400)$$

Equation 4. Driver Exposure Risk to Rockfall

Where:

L = Length of exposed road cut (m)

N = Traffic count (AADT)

V = Vehicle speed (m/s)

6 Tools for Risk and Resilience Assessment

This section documents and provides an overview of publicly available risk and resilience tools, including spreadsheet models, stand-alone desktop applications, and web-based tools.

6.1 Spreadsheet models

Risk Registers: Risk registers are an extremely common way for State DOTs to assess, usually qualitatively, the consequence and likelihood of an event happening. States incorporate risk registers into their TAMPs to identify priority items and correlate appropriate strategies and benefit and cost estimates. While some have specific risk management chapters, others just create their risk register as an overview of critical assets. States like West Virginia and Florida conduct workshops to compile their initial risk registers (FDOT Transportation Asset Management Plan, 2019; WV DOT Transportation Asset Management Plan, 2019).

Often, an Excel spreadsheet is used, recording the likelihood and severity of consequences for each risk. Typically, a 5 x 5 matrix is employed, intersecting

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likelihood with severity to calculate a risk ranking. FHWA's Center for Innovative Finance Support (FHWA, 2015) provides an example of a qualitative risk matrix (see Figure 28). NCHRP 08-36(126) (Patrick, Senesi, & Molenaar, 2016) details developing a risk register.

Representative Cost Impact Assessment Matrix						
		Cost Consequence				
		5	4	3	2	1
Probability	**Scale**	> 25%	10% - 25%	3% - 10%	1% - 3%	<1%
	5 - > 70%	High	High	High	Medium	Low
	4 - 40% - 70%	High	High	Medium	Medium	Low
	3 - 20% - 40%	High	Medium	Medium	Low	Low
	2 - 5% - 20%	Medium	Medium	Low	Low	Low
	1 - 0% - 5%	Low	Low	Low	Low	Low

Figure 28. Qualitative Risk Matrix (FHWA, 2015)

VAST: The U.S. DOT's Vulnerability Assessment Scoring Tool (VAST) (Bhat, et al., 2015) is an Excel spreadsheet implementation of the FHWA VAAF. The tool is designed to help planners at state DOTs, and MPOs assess the vulnerability of their transportation assets to climate stressors. It is an indicator-based tool that assigns an index value to three factors:

- Exposure
- Sensitivity
- Adaptive capacity

Index values for the three factors are summed to calculate a composite risk score.

PennDOT developed its spreadsheet tool to implement VAAF as part of its Extreme Weather Vulnerability Study (PennDOT, 2017). Relative index values representing factors such as AADT and functional class are manually entered for each roadway segment. The inputted values are multiplied by the weights, shown in Figure 29.

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Risk Assessment Calculation

Item	Enter Weight	Default*	
Exposure	3	3	*Overall Weight Factor for Exposure Variables*
Rainfall Causing Event	0.5	0.5	
In FEMA 1% Flood Plain	0.5	0.5	*Sub factor weighting*
Sensitivity	3	3	*Overall Weight Factor for Sensitivity Variables*
Bridge Scour	0.4	0.4	
OPI	0.4	0.4	*Sub factor weighting*
Deficient Pipe	0.2	0.2	
Consequence	4	4	*Overall Weight Factor for Consequence Variables*
Traffic Volume	0.4	0.4	
Truck Volume	0.2	0.2	
FC	0.3	0.3	*Sub factor weighting*
Detour	0.1	0.1	

Update Statewide and District Rankings Based on Revised Weights

** Current mapping of results based on default values*

INSTRUCTIONS:

Step 1 *Enter overall weights for the categories: Exposure, Sensitivity and Consequence (Sum should equal 10)*

Step 2 *Enter weights for sub factors (Sum within each category should equal 1.0)*

Step 3 *Click button to rank all road segments within statewide and District sheets*

Step 4 *View remaining Sheets (blue) for statewide and district rankings (Note maximum score = 100)*

Figure 29. PennDOT extreme weather vulnerability risk assessment tool (PennDOT, 2017)

HYRISK: Sponsored by the FHWA, HYRISK (Pearson, Stein, & Jones, 2000) is an Excel-based, scour risk assessment tool for bridges. The tool requires inputs from the National Bridge Inventory (NBI) to calculate the probability of failure due to scour (see Table 25. Bridge probability from scour using HYRISK Model (Pearson, Stein, & Jones, 2000)). HYRISK uses the following NBI Items:

- Item 26: Functional class
- Item 43: Structure type
- Item 60: Substructure condition rating
- Item 61: Channel and channel protection condition rating
- Item 71: Waterway adequacy

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- Item 113: Scour-critical bridges

Table 25. Bridge probability from scour using HYRISK Model (Pearson, Stein, & Jones, 2000)

Scour Vulnerability *(from Table 14)*	Overtopping Frequency *(from Table 13)*			
	Remote (R)	*Slight (S)*	*Occasional (O)*	*Frequent (F)*
(0) Failed	1	1	1	1
(1) Imminent failure	0.01	0.01	0.01	0.01
(2) Critical scour	0.005	0.006	0.008	0.009
(3) Serious scour	0.0011	0.0013	0.0016	0.002
(4) Advanced scour	0.0004	0.0005	0.0006	0.0007
(5) Minor scour	0.000007	0.000008	0.00004	0.00007
(6) Minor deterioration	0.00018	0.00025	0.0004	0.0005
(7) Good condition	0.00018	0.00025	0.0004	0.0005
(8) Very good condition	0.000004	0.000005	0.00002	0.00004
(9) Excellent condition	0.0000025	0.000003	0.000004	0.000007

CDOT's Risk and Resilience Excel Spreadsheet Tool: CDOT developed a Risk and Resilience Analysis Procedure to calculate annual risk to highway infrastructure from the following threats: flood, rockfall, and scour. Based on this procedure, CDOT developed an Excel Spreadsheet tool (Colorado DOT, 2020). The CDOT Risk and Resilience tool is a deterministic model and calculates annual owner and user risk for roads, bridges, and culverts.

6.2 Software Tools

Some software tools are also available to estimate risk and resilience to certain assets from certain threats. However, these tend to be more data-intensive and require higher knowledge and capabilities. Some of these tools include:

HAZUS-MH: This tool, considered the state-of-the art risk tool for natural hazard risk assessment, is a GIS-based tool provided freely to the public by the Federal Emergency Management Administration (FEMA). However, the tool is an add-in to ESRI's ArcGIS Desktop application, requiring a licensing fee. The latest version, 4.0, was released in 2017. The HAZUS earthquake model (FEMA, 2020) includes fragility curves for roads and bridges. The HAZUS flood model (FEMA, 2018) can generate depth grids that can estimate flood extent and the likelihood of overtopping. The flood model also includes a scour risk model for bridges but does not include models to address damage to road surfaces. Quantitative outputs for the earthquake model include estimates of direct losses, calculated as a fraction of the replacement value. For the flood model, estimated losses are computed for bridges but not roads. HAZUS-MH is also a resilience assessment tool in that it includes restoration curves for bridges in the earthquake (FEMA, 2020) and flood models (FEMA, 2018). The earthquake restoration curve is

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based on expert opinion and conforms to a normal cumulative distribution function. The flood restoration curve is based on damage state versus time to rebuild.

REDARS 2: Developed by MCEER under the sponsorship of FHWA, REDARS2 stress tests bridges, tunnels, and retaining structures under seismic loading. The software includes the capability to simulate traffic volume, pre-, and post-event (Werner, et al., 2006).

6.3 Web-based Application Tools

Besides spreadsheets and software, there are also web-based tools or models to calculate risk. Examples of these tools are:

Vermont Transportation Resilience Planning Tool (TRPT) (VTRANS, n.d.)**:** The Vermont TRPT is a web map that enables the user to visualize relative flood risk to embankments, culverts, and bridges. The potential risk is estimated based on criticality and asset vulnerability and proposes mitigation alternatives to reduce risk. The level of risk is indicated by color coding roadway segments: low (green), medium (orange), and high (red). Low levels of vulnerability may mean slight damage due to inundation or minor erosion, whereas high vulnerability may mean complete failure of the asset due to severe erosion or deposition (VTRANS, 2019). Figure 30 shows a representation of assets and their different risk levels.

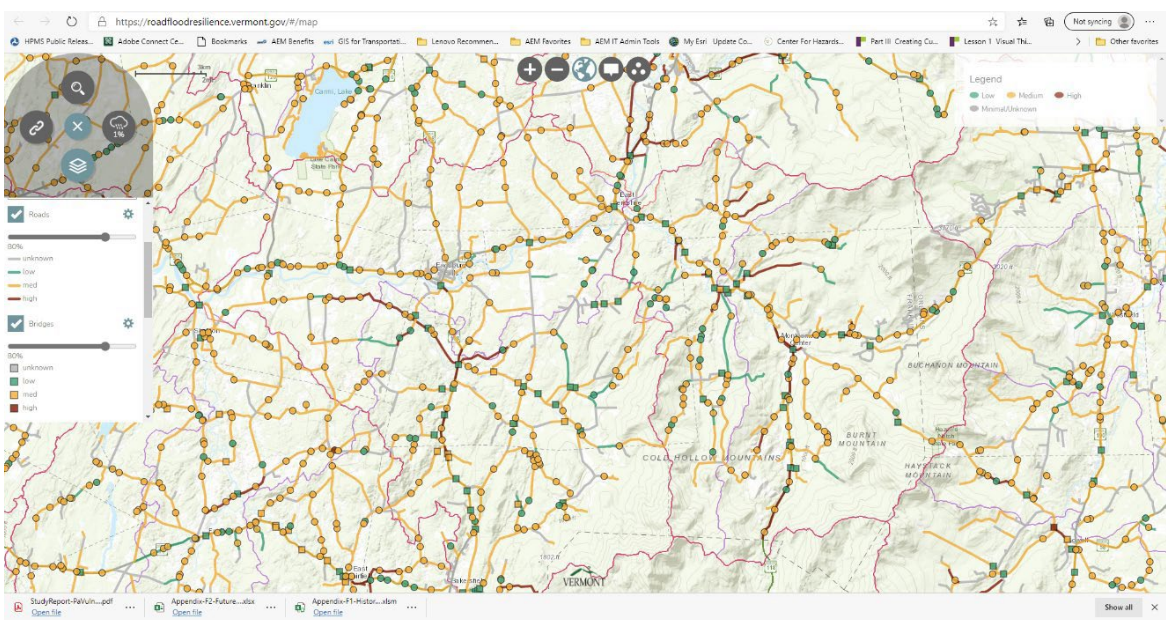

Figure 30. Screenshot of Vermont TRPT (VTRANS, 2019)

Boston Harbor Flood Risk Model (BH-FRM) (Massachusetts DOT, n.d.)**:** This is a dynamic flood model developed by Massachusetts DOT (MassDOT) under FHWA's

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Climate Resilience pilots. This model was developed to determine inundation risk and flooding pathways. This tool simulates the effects of tides, storm surge, wind, waves, river discharge, sea-level rise, and climate scenarios.

ESRI's Resilience Dashboard is a preconfigured web-based dashboard that runs in ArcGIS Online (ESRI's cloud). Designed for emergency management, the dashboard includes drop-down windows to enable users to filter the features displayed by asset class and a limited number of attributes relevant to resilience and criticality, such as "importance to the community – high" or "dependent upon flood pumps – yes." The tool displays an overall resilience ranking, aggregated by county (ESRI, n.d.).

Many transportation agencies are currently developing their models and tools to estimate risk and resilience to different assets and threats. Some agencies are more advanced in this process than others. In addition, some of these initiatives are developed based on sponsorships from FHWA or TRB, while other agencies invest in their resilience programs to build these tools.

The following tools are web tools developed and hosted by the US Army Corps of Engineers (USACE).

Sea Level Change Calculator: The USACE Sea Level Change Calculator generates sea level change projections for a user-selected NOAA sea-level gauge (USACE, 2017). The user can print out the curve of the change in sea level over time, either as a graph or table.

Sea Level tracker: The USACE Sea Level Tracker tool "does not predict future water levels. Rather, the tool offers smoothed analysis of historical sea-level behavior and the measured trends at a user-selected gauge" (USACE, n.d.). The tool includes a map window, data visualization window (trend line), and data table view. The user first selects a location and then a datum: (Mean Sea Level (MSL), Mean High Water (MHW), or Mean of the Higher High-Water Height (MHHW)). The output is a graph of the trend line from 1975 to the present.

Climate Hydrology Assessment Tool: The USACE Climate Hydrology Assessment Tool generates a trend line showing the change in peak streamflow based on climate change projections (USACE, n.d.).

6.4 Methods for Developing Recovery Strategies

Recovery refers to the time it takes for an asset, corridor, or system to return to normal after a disruption. The National Disaster Recovery Framework (FEMA, 2020) defines four phases: 1) preparedness (pre-disaster), 2) short-term (days), 3) intermediate (weeks to months), and 4) long-term (months to years) (see Figure 26). The time it takes for a system to recover is one possible metric for resilience, as it measures how well planners

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are meeting the needs of the public to resume the use of damaged infrastructure (NCHRP). On this theory, academic studies have developed measure of resilience (MOR) models that incorporate recovery time. Two studies develop these models on highways using freight metrics. The first modeled the ability of intermodal freight networks to withstand and recover from disruptors (Chen & Miller-Hooks, 2011) and the second studied the reduction of service and recovery levels to pre-event conditions along the I-90/I-94 corridor in Wisconsin during two weather events (Adams, Bekkem, & Toledo-Duran, 2012).

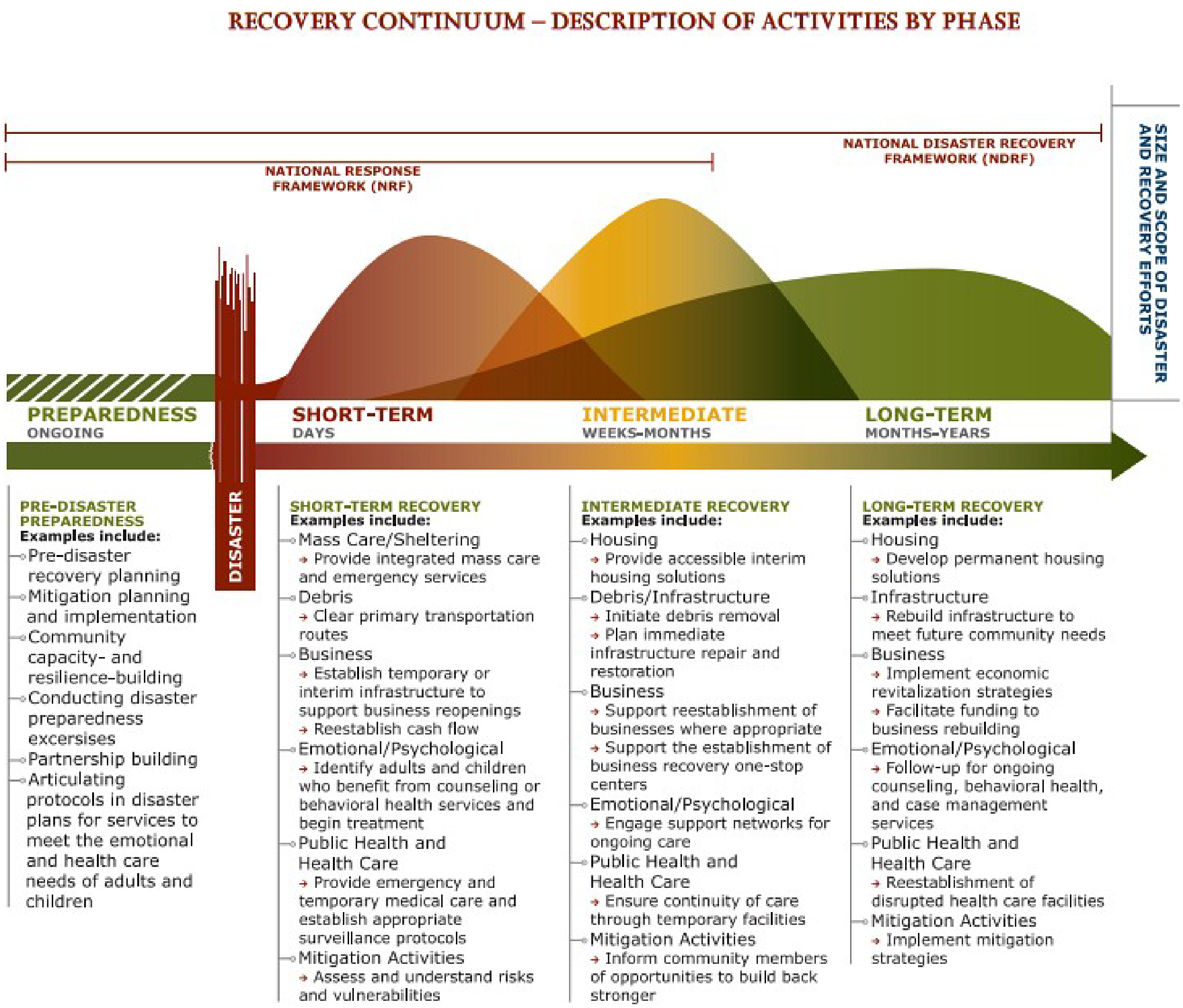

Figure 31. National Disaster Recovery Framework (FEMA, 2020)

Though these studies provide a theoretical framework for understanding recovery, a gap remains between this theory and the practical strategies planners can use to quicken recovery after a hazard event. One source for these strategies is a report from

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AASHTO released in May 2018 on Resiliency Case Studies: State DOT Lessons Learned (WSP). This report reviewed eight extreme weather events, including tropical storms, hurricanes, flooding events, rock falls, ice storms, tornados, and landslides, and cataloged how state DOTs responded to these events. In particular, it contained lessons on the emergency response relevant to recovery strategies in the aftermath of a hazard event. This report suggested the following steps that DOTs could take:

- Enter into contracts and Memorandums of Agreements (MOA) before any emergency to assist with the response and expand department capacity. This could include areas such as debris removal and flooding response.
- Use social media during emergencies to disseminate information directly to the public, in addition to traditional mediums such as TV, radio, and electronic signage.
- Prior to an emergency, have a financial accounting system to maximize access to and benefits from relief funds.
- Work with emergency management departments to have a centralized emergency management center to streamline the response.
- Set up partnerships with GPS and mapping applications to disseminate information about road closures and detours.
- Prioritize public safety in all parts of an emergency response.

Additionally, NCHRP Research Report 931, *A Guide to Emergency Management at State Transportation Agencies*, places transportation agencies within the larger context of emergency response (NCHRP Report 931: A Guide to Emergency Management at State Transportation Agencies, 2020). Using a framework known as the Incident Command System, this guidebook explains the roles and responsibilities likely to face transportation agencies during an emergency. It provides details and examples of policies and plans that the agencies should have to help agencies prepare for coordinated emergency response.

Finally, NCHRP Report 753, *A Pre-Event Recovery Planning Guide for Transportation*, helps agencies with their pre-event planning process that can assist in developing recovery strategies (Bye, Yu, Shrivastava, & Leeuwen, 2013). This guidebook emphasizes collaboration through informal and formal networks, pre-existing plans, and preventative infrastructure improvement plays in recovery strategies. It also summarizes how pre-event planning can be a part of other planning processes, such as asset management and risk management plans.

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6.5 Methods for Risk Management

Risk management is the process of identifying, measuring, managing and mitigating risks that might threaten goals and initiatives that an organization pursues. It is a natural complement to performance management and asset management. Where agencies use those two tools to set goals and initiatives, agencies use risk management to catalog and mitigate factors that may prevent those goals and initiatives from succeeding.

Risks are uncertain events that, if they occur, can affect at least one goal or objective of a project, program, or enterprise (Risk Management Guidance). Risks can either be negative (and are called *threats*) or positive (called *opportunities*). Strategies to manage threats and hazards, such as avoiding, transferring, or mitigating the risk, reduce the likelihood that it will occur and/or the impact it will have if it occurs. Strategies to manage opportunities, such as exploiting, sharing, or enhancing the risk, take the opposite approach to threats and seek to make them more likely to occur and/or increase the impact if it occurs. At a certain point, however, agencies must accept the risks, whether they are threats or opportunities, and direct planners to track and monitor those risks.

NCHRP 08-93 provides a risk management guide for State DOTs (Proctor, Varma, & Roorda). It gives DOTs detailed guidance for establishing an enterprise risk management policy tailored to their environment. Some benefits provided by risk management that this guide emphasizes include financial strategies because agencies benefit from clear processes used to allocate resources, and communication benefits, because agencies can use risk as a framework to explain goals and implement strategies.

This guidebook contains many risk management strategies and applies them to different situations that a State DOT may face. A selection of some of the significant strategies covered in the guidebook include:

- Put an enterprise risk management process in place that: (1) incorporates levels of risk (from strategic risks across the enterprise to risks associated with specific department activities): (2) provides staff with the tools and training to implement the process; and (3), integrates risk management into agency processes at regular intervals.
- Use various techniques to identify risks, such as brainstorming workshops with staff, structured interviews, the development of checklists, and step-by-step process reviews.
- As risks are identified, examine the environment surrounding that risk, documenting both the external factors that may influence an objective and the internal environment with different components involved in responding to that risk.

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- Organize risks into categories such as health and safety, occupational, economic, political, regulatory, information, natural environment, fraud or malfeasance, and litigation risks.
- Once categorized, determine the cause of risks, which can be done through workshops or simulations, focusing on determining the root cause.

Other sections of this literature review cover additional strategies covered in the guidebook, such as risk registers and quantitative methods for estimating risk consequences and likelihood.

6.6 Methods to Improve System Resilience

Resilience is defined by the FHWA as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions (FHWA, 2014)." The FHWA Office of Planning, Environment, and Realty maintains a website on resilience (Resilience). It is in line with the FHWA's work to increase the health and longevity of the Nation's highways by assessing vulnerabilities, considering resilience in the transportation planning process, incorporating resilience in asset management plans and long-range transportation plans, addressing resilience in project development and design, and optimizing operations and maintenance practices. This website maintains guidance, framework and pilots, and research projects to support this work.

One of the resources on this website is a white paper summarizing how State DOTs and MPOs incorporate resilience into the transportation planning process (Dix, Zgoda, Vargo, Heitsch, & Gestwick, 2018). This document summarizes how these organizations define resilience, which agencies incorporate resilience into their planning process, and why and how they do so. It is this last question, the "how," where there is the most information. The paper provides a variety of perspectives on the goals of resilience planning, the assessment of problems or needs, performance measures and targets set out in the plans, and strategies available (including policy-based, flooding-related, operational, and partnership-based strategies). However, the paper notes that substantive information regarding the implementation of strategies is not yet available.

Resilience strategies specific to highway systems generally revolve around two categories: (1) design guidelines; and (2) flooding or stormwater management. Design guidelines can implement policy-based strategies, such as how climate change may impact vertical clearance for bridges or the monitoring of pavement conditions. Flooding and stormwater management strategies reflect concerns about how the

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highway system will respond to hazards, such as significant storms, or shifting environmental conditions, such as increases in river flow or rising sea levels. The AASHTO report on resiliency case studies notes the importance of updating hydraulics manuals and strategic plans (WSP). Overall, incorporating climate risk and variability into asset management practices and prioritization of resources to maintain and reinforce the most vulnerable and critical assets can improve transportation system resilience.

FEMA maintains an Office of Resilience Integration and Coordination to ensure that agency activities across Resilience are unified and coordinated with the FEMA regional offices, other federal agencies, and partnering industry associations. The Resilience Office also provides training through the National Preparedness Directorate for the nation's first responders and helps communities prepare for, respond to, and recover from disasters (FEMA Resilience, n.d.).

NCHRP 08-36(73) recommends planning for disruptions for improving system resilience, including detour management plans and continuity of operations plans (NCHRP 08-36, Adding Resilience to the Freight System In Statewide and Metropolitan Transportation Plans: Developing a Conceptual Approach, n.d.). Report recommendations also suggest developing tools to assess the dynamic performance of integrated passenger and freight transportation systems by incorporating resilience into travel demand models. Another critical consideration includes incorporating adaptive capacity to determine system capacity and redundancies while preparing plans to reallocate resources as required to address potential disruptions.

Consistent and reliable funding is also a key challenge when improving system resilience. Programs that fund highway expenditures, such as the National Highway Performance Program and the Surface Transportation Block Grant Program, make expenditures that fund improved system resilience eligible for funding. The Emergency Relief Program funds can also be used on repairs that will enhance the resilience of Federal-aid highways (FHWA Funding, n.d.). To be approved, State DOTs must demonstrate that those repairs are economically justified by weighing the cost of improvements against the risk of recurring damage and the cost of future repair.

7 Tracking Mechanisms for Risk and Resilience Metrics (Annual Reports, Story Maps, and Dashboards)

Various types of tracking mechanisms have been developed to evaluate and process risk and resilience metrics. States use these mechanisms to prepare risk management efforts and incorporate resilience into their systems. In addition to traditional tracking

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methods such as written reports and spreadsheets, transportation agencies rely more on GIS to produce vivid story maps and dashboards.

7.1 Recurring Reports

Annual reports help see the yearly impact of various assets and allow states to track progress and implement better mitigation efforts moving forward. Minnesota's "MinnesotaGo" program is a program aligning the MnDOT system with the public regarding quality of life, economy, and the natural environment (Minnesota DOT, 2022). They developed a "Trend Library" that showcases metrics and annual updates, allowing the continual impact over the years to be easily understood.

It should be noted that these various tracking mechanisms are shaped for the agency, reflecting their characteristics, priorities, and data, but can be transferable and utilized by other agencies to improve their own risk and resilience metrics further.

Furthermore, snapshot observations of these metrics that are memorialized, such as in an annual report, are also used in public communication initiatives as content for brochures and white papers to inform the public more strategically on agency consideration of risks and resilience measures. An example of such a communication is the 2019 "Why Should We Care About Roads?" brochure created VTrans (Agency, 2019). A highlight document of this format can effectively communicate core values and highlight goals or progress.

7.2 Story Maps

ArcGIS *StoryMaps* is an ESRI proprietary web application that enables users to integrate digital maps with narrative content and other multi-media. ESRI's Story Map Series Gallery includes examples of story maps by state and local transportation agencies (ESRI, 2021).

7.3 Dashboards

In addition to map views, GIS web applications can also include widgets that can dynamically display quantitative measures such as traffic counts or accidents. The Hampton Roads Resilience Project dashboard (see Figure 31) consists of a map view of point locations for projects, symbolized by color by project types, such as drainage improvements or stormwater management. To the left, there are widgets to display quantitative data in terms of cost in millions of dollars by project type and status.

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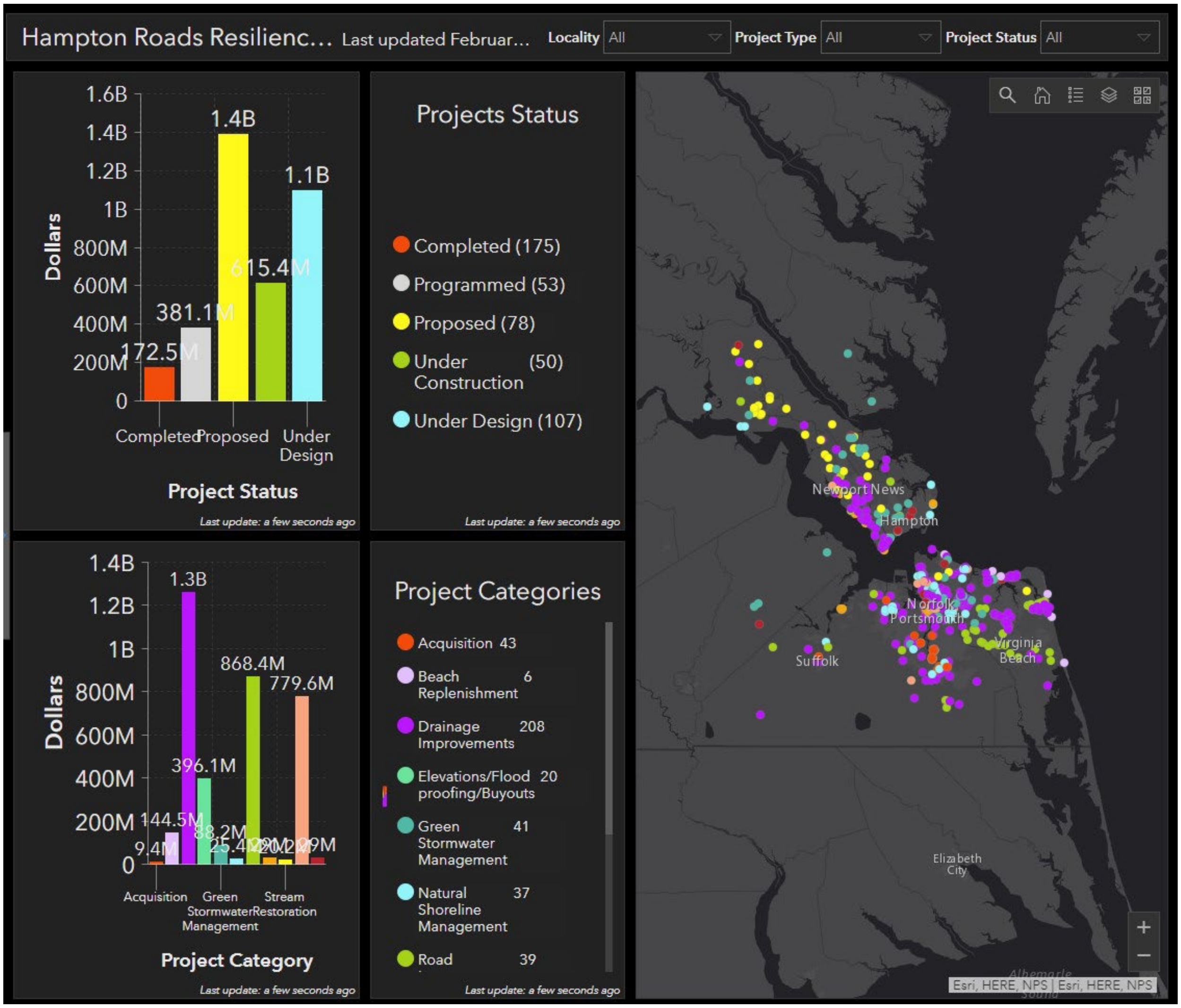

Figure 32. Hampton Roads Resilience Project Dashboard (Hampton Roads Transportation Planning District Commission, 2014)

Another example of a dashboard is the Southeast Michigan Council of Government's (SEMCOG) Flooding Risk Tool Dashboard (Southeast Michigan Council of Governments (SEMCOG) and Michigan DOT (MDOT), 2020) (see Figure 32). In the map view, road segments are symbolized by color by risk rating: low (green), medium (gold), and high (red). The widgets to the right include a pie chart illustrating the percentage of roads rated as low, medium, or high risk; the total number of road assets, bridges, culverts, and pump stations; and a list of the top 5 road segments at risk with associated vulnerability and criticality scores.

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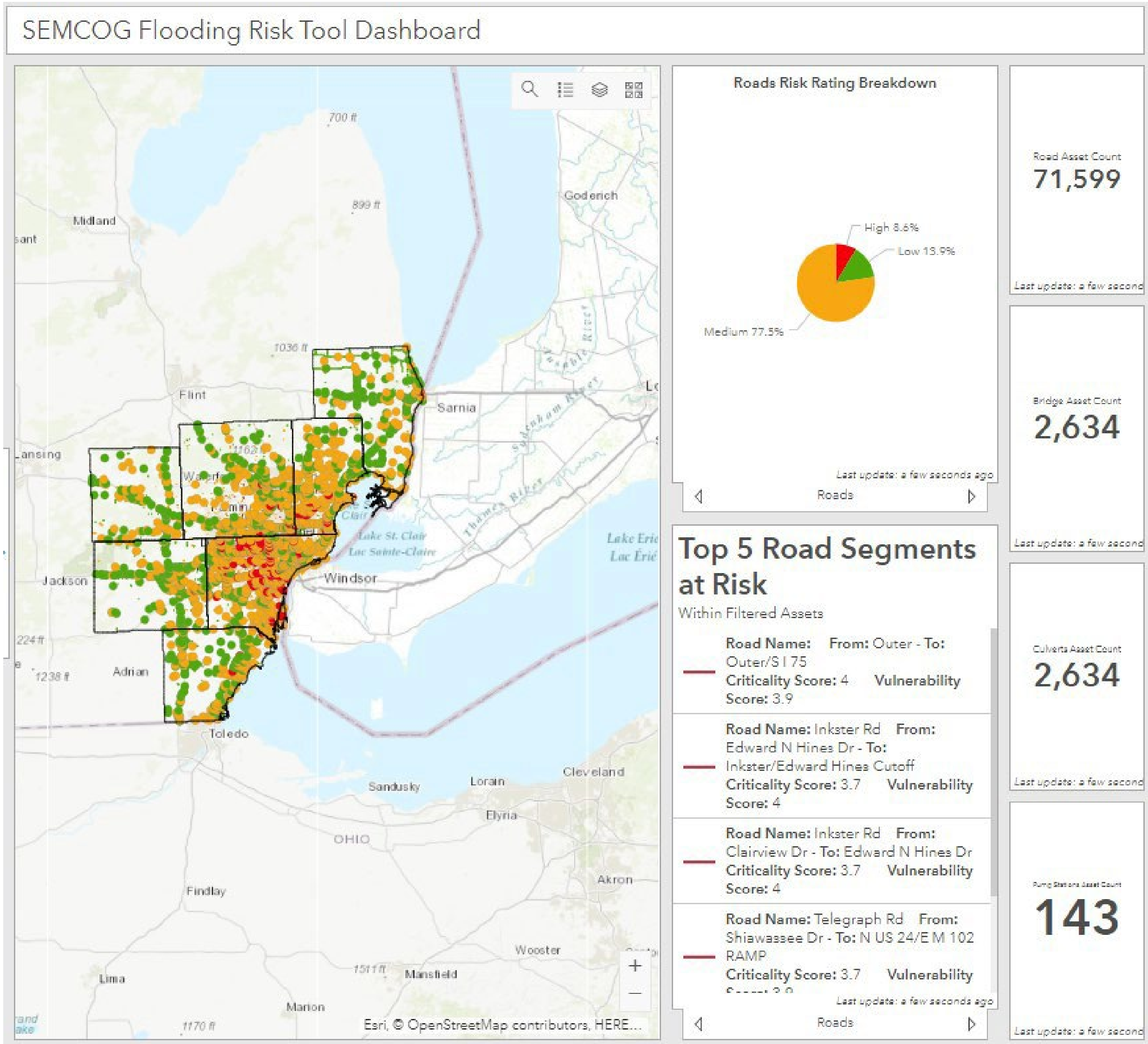

Figure 33. SEMCOG Flooding Risk Tool Dashboard (Southeast Michigan Council of Governments (SEMCOG) and Michigan DOT (MDOT), 2020)

8 Barriers and Constraints for Implementation of Quantitative Risk and Resilience Assessment Methods

Barriers to implementing risk and resilience methods include the lack of robust evaluation and validation processes, availability of supporting data and tools, and limited technical capacity and knowledge base to implement quantitative risk and resilience assessments. Among the barriers to incorporating resilience assessments in transportation planning is the lack of evaluation methods and criteria for monitoring existing plans that use resilience strategies. The review of how DOTs and MPOs use

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resilience assessments in their planning processes revealed that only a limited number of DOTs and MPOs include resilience-related performance measures (Dix, Zgoda, Vargo, Heitsch, & Gestwick, 2018). Such performance measures have not been tracked for long enough to deduce any lessons on monitoring and reporting. Among those agencies that have implemented resilience assessments, their monitoring metrics relate to the frequency of these assessments being updated. Therefore, a review of how states are monitoring the implementation of resilience assessments remains a significant gap.

Conducting quantitative risk and resilience assessments require a substantial amount of data. A possible barrier to implementation is the management and collection of these data types in a centralized and systematic database. For example, the FHWA's report on Vulnerability Assessment and Adaptation Framework notes that complete data may not be available for all assets (FHWA Vulnerability Assessment and Adaptation Framework, 3rd Edition, n.d.). Though a considerable amount of data is available along with major systems such as the NHS, more granular data, such as culvert slope, as-built information, and flood history, may not be available for roads outside the NHS. This can hinder vulnerability assessments for minor arterial and collector roads.

A more systematic and comprehensive review of recovery strategies can help return conditions to normal after a hazard impacts service. There has been ample preparation for hazards in emergency management, including guidebooks and exercises to make plans in collaboration with emergency management departments. However, pre-event recovery strategies for State DOTs are needed. NCHRP Report 753, A Pre-Event Recovery Planning Guide for Transportation, was published in 2013 (Bye, Yu, Shrivastava, & Leeuwen, 2013). Though it does include strategies for developing networks and plans with other agencies, it does not incorporate the progress made in topics like asset management, performance management, and risk assessments that have been accomplished since that time. These types of plans can be used to help improve the post-hazard recovery response.

Finally, numerous risk and resilience analysis tools have been developed in recent years that vary significantly in their complexity. Though this represents an advancement in the sophistication of these techniques, it can also act as a barrier to implementation. For example, in NCHRP 08-93, *Guidebook for Risk Analysis for State DOTs*, John Milton (Washington State DOT) explained complex risk management tools were discontinued because of their complexity and lack of transparency (Proctor, Varma, & Roorda). The effort to develop increasingly sophisticated risk assessment tools needs to be balanced with ease of use for end-users and transparency about how these tools work. Quantitative risk and resilience methods have been researched over the past two decades, with only a few techniques successfully adopted into applied practice. Standardized and well-understood methods may need to be adopted using cooperative

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research efforts and coordination among academic researchers and practitioners to enable the transition for a widespread application.

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References

AASHTO. (2013). *AASHTO Transportation Asset Management Guide – Executive Summary.* Retrieved from https://www.fhwa.dot.gov/asset/pubs/hif13047.pdf

AASHTO. (2016). *Guide for Enterprise Risk Management: Quick Guide.* AASHTO.

AASHTO. (2016). *Understanding transportation resilience: A 2016 - 2018 roadmap for security, emergency management, and infrastructure protection in transportation resilience.* Washington, D.C.

Abunemeh, M., El meouche, R., Hijaze, I., Mebarki, A., & Shahrour, I. (2017). Hazards, Vulnerability and Interactions at Construction Sites: Spatial Risk Mapping. *Journal of Information Technology in Construction, 22*(4), 63-79.

Adams, T. M., Bekkem, K. R., & Toledo-Duran, E. J. (2012). *Freight Resilience Measures. Journal of Transportation.* Retrieved from https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29TE.1943-5436.0000415

Adaptation Clearing House. (2015). *U.S. Department of Transportation's Vulnerability Assessment Scoring Tool (VAST).* Retrieved from https://www.adaptationclearinghouse.org/resources/u-s-department-of-transportation-s-vulnerability-assessment-scoring-tool-vast.html

Adger, W. N. (2006). Vulnerability. *Global Environmental Change, 16*(3), 268-281.

AEM Corporation. (2017, November 30). *I-70 Corridor Risk & Resilience Pilot Final Report.* Retrieved from https://www.codot.gov/programs/planning/documents/plans-projects-reports/reports/i70rnr_finalreport_nov302017_submitted_af.pdf

AEM Corporation. (2020). *Colorado Department of Transportation Risk and Resilience Procedure: A manual for Calculating Risk to CDOT Assets from Flooding, Rockfall, and Fire Debris Flow.* Retrieved from https://www.codot.gov/programs/planning/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf

Agency, V. T. (2019, September). *Why Should We Care About Roads?* Retrieved from https://vtrans.vermont.gov/sites/aot/files/planning/documents/TAMP%20Brochure-SCROLLING.pdf

Alder, R., Wirth, J., Moser, A., Busch, G., Henrie, J., & Slooten, N. V. (2020). *UDOT Asset Risk Management Process.* Salt Lake City, UT: Utah Department of Transportation.

Draft - Not for Distribution

Anandhi, A., & Kannan, N. (2018). Vulnerability Assessment Of Water Resources – Translating a Theoretical Concept to an Operational Framework Using Systems Thinking Approaching a Changing Climate: A Case Study In Ogallala Aquife. *Journal of Hydrology, 557*, 460-474.

Anderson, T. (2019). *ADOT Transportation Asset Management Plan.* Phoenix, AZ: Arizona Department of Transportation .

Argyroudis, S., Mitoulis, S., Kaynia, A. M., & Winter, M. G. (2018). Fragility assessment of transportation infrastructure systems subjected to earthquakes. *Geotechnical Earthquake Engineering and Soil Dynamics V: Numerical Modeling and Soil Structure Interaction.* , 174-183.

Asam, S., Bhat, C., Dix, B., Bauer, J., & Gopalakrishna, D. (2015). *Climate Change Adaptation Guide for Transportation Systems Management, Operations and Maintenance.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration. Retrieved from http://www.dot.state.oh.us/Divisions/Operations/Traffic-Management/TSMO%20Docs/FHWA%20Climate%20Change%20Adaptation%20Guide%20for%20Transportation%20Systems%20Management%20Operations%20and%20Maintenance.pdf

ASME. (2009). *All-hazards risk and resilience: Prioritizing critical infrastructures using the RAMCAP Plus approach.* New York: ASME Innovative Technologies Institute, LLC.

AWWA. (2010). *J100-10 RAMCAP Standard for Risk and Resilience Management for Water and Wastewater.* Denver, CO: American Water Works Association.

AzDOT. (2019, February). *Asset Management, Extreme Weather, and Proxy Indicators Pilot Project*. Retrieved from https://azdot.gov/sites/default/files/2019/07/Asset-Mgmt-Extreme-Weather-and-Proxy-Indicators-Pilot-Project.pdf

Battelle. (2007). *Evaluation of system's available redundancy to compensate for loss of transportation assets resulting from natural disaster or terrorist attacks. Report of the National Surface Transportation Policy and Revenue Study Commission: Transportation for Tomorr .* National Surface Transportation Policy and Revenue Study Commission.

Berdica, K. (2002). An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy, 9*, 117-127.

Bhat, C., Hyman, R., Kafalenos, R., Beucler, B., Choate, A., & Rodehorst, B. (2015, September 17). *FHWA Vulneraibliity Tools.* Retrieved December 9, 2020, from http://onlinepubs.trb.org/onlinepubs/conferences/2015/ClimateChange/67.CassandraBhat.pdf

Draft - Not for Distribution

Bosworth, R. C., Hunter, A., & Kibria, A. (2017). *The Value of a Statistical Life: Economics and Politics.* Logan, UT: Strata.

Bratvold, R. B., & Begg, S. H. (2010). *Making Good Decisions.* Richardson, TX: Society of Petroleum Engineers.

Bruneau, M., & Reinhorn, A. (2006). Overview of the resilience concept. *National Conference on Earthquake Engineering.* San Francisco.

Bruneau, M., Chang, S. E., Eguchi, R. T., & Lee, G. C. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra, 19*, 733-752.

Bye, P., Yu, L., Shrivastava, S., & Leeuwen, S. v. (2013). *NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation.* Washington, D.C.: The National Academies Press. Retrieved from https://nap.nationalacademies.org/catalog/22527/a-pre-event-recovery-planning-guide-for-transportation

Caltrans. (2018, April 11). *Environmental Risk Register Guidance.* Retrieved from https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/ser/f0005505-env-risk-mngmt-a11y.pdf

Caltrans. (2019, May). *California Transportation Asset Management Plan Fiscal Years 2017/18-2026/27.* Retrieved from https://dot.ca.gov/-/media/dot-media/programs/asset-management/documents/20190726-am-finalcaliforniatamp-a11y.pdf

Caltrans Division of Research, Innovation and System Information. (2015, July 22). *Application of Quantitative Risk Management Practices to Project Development: A Survey of State Practice and Related Research*. Retrieved from https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/application-of-quantitative-risk-management-practices-pi-a11y.pdf

Calvert, S., & Snelder, M. (n.d.). *A methodology for road traffic resilience analysis and review of related concepts.* Retrieved from https://www.tandfonline.com/doi/full/10.1080/23249935.2017.1363315

Cambridge Systematics. (2011). *Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure.* Retrieved from https://www.njtpa.org/NJTPA/media/Documents/Planning/Regional-Programs/Studies/Climate%20Change%20Vulnerability%20and%20risk%20Assessment/CCVR_REPORT_FINAL_4_2_12_ENTIRE.pdf?ext=.pdf

Draft - Not for Distribution

Cambridge Systematics and ICF International. (2015). *Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure - Final Report.* Retrieved from http://austintexas.gov/sites/default/files/files/CAMPO_Extreme_Weather_Vulnerability_Assessment_FINAL.pdf

Cape Cod MPO. (2015). *Cape Cod 2016 Regional Transportation Plan 2016-2040.* Barnstable, MA: Cape Cod Metropolitan Planning Organization.

CDOT. (2019). *Risk-Based Asset Management Plan Version 2*. Colorado Department of Transportation.

CDOT. (n.d.). *Risk and Resilience Analysis Procedure 2020*. Retrieved from https://www.codot.gov/programs/planning/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf

CFR 2017 Title 23 Part 515. (n.d.). Retrieved from https://www.govinfo.gov/content/pkg/CFR-2017-title23-vol1/pdf/CFR-2017-title23-vol1-part515.pdf

Chen, A., Yang, C., Kongsomsaksakul, S., & Lee, M. (n.d.). *Network-based Accessibility Measures for Vulnerability Analysis of Degradable Transportation Networks.* Retrieved from https://www.researchgate.net/publication/5153107_Network-based_Accessibility_Measures_for_Vulnerability_Analysis_of_Degradable_Transportation_Networks

Chen, L., & Miller-Hooks, E. (2011, August 18). *Resilience: An Indicator of Recovery Capability in Intermodal Freight.* Retrieved from https://pubsonline.informs.org/doi/10.1287/trsc.1110.0376

Chen, S., Ioannis, G., Jamie, P., & Barbosa, A. (n.d.). *Multiple-Hazard Fragility and Restoration Models of Highway Bridges for Regional Risk and Resilience Assessment in the United States: State-of-the-Art Review*. Retrieved from https://www.researchgate.net/publication/308755769_Multiple-Hazard_Fragility_and_Restoration_Models_of_Highway_Bridges_for_Regional_Risk_and_Resilience_Assessment_in_the_United_States_State-of-the-Art_Review

Code of Federal Regulation. (n.d.). Retrieved from https://www.ecfr.gov/cgi-bin/text-idx?c=ecfr;sid=e2662fc63c225d496d1fa6ce22ea6cb8;rgn=div5;view=text;node=23%3A1.0.1.5.11;idno=23;cc=ecfr#se23.1.450_1306

Colorado DOT. (2020). *CDOT Resilience Program*. Retrieved December 10, 2020, from https://www.codot.gov/programs/planning/cdot-resilience-program

Draft - Not for Distribution

Computer Security Resource Center Information Technology Laboratory. (n.d.). *Vulnerability*. Retrieved January 13, 2020, from https://csrc.nist.gov/glossary/term/vulnerability

Corona, C., Lopez-Saez, J., Favillier, A., Mainieri, R., Eckert, N., Trappmann, D., . . . Berger, F. (2017). Modeling rockfall frequency and bounce height from three-dimensional simulation process models and growth disturbances in submontane broadleaved trees. *Geomorphology, 281*, 66-77.

Council on Foreign Relations. (2021). *Cyber Operations Tracker*. Retrieved from https://www.cfr.org/cyber-operations/

Council, N. R. (2012). *Disaster Resilience: A National Imperative.* National Academies Press. Retrieved from http://nap.edu/13457

CSIS (Center for Strategic & International Studies). (2021). *Significant Cyber Incidents*. Retrieved from https://www.csis.org/programs/strategic-technologies-program/significant-cyber-incidents

Curtis, J. A., Dailey, J. S., D'Angelo, D., DeWitt, S. D., Graf, M. J., Henkel, T. A., . . . Rocco, R. E. (2012). *Transportation Risk Management: International Practices for Program Development and Project Delivery.* FHWA. Retrieved from https://international.fhwa.dot.gov/scan/12029/12029_report.pdf

DHS. (2009). *National infrastructure protection plan.* Washington, D.C.: United States Department of Homeland Security.

DHS. (2010). *Risk and Resilience: Exploring the relationship.* Arlington, VA: United States Department of Homeland Security.

DHS. (2012). *Threat and Hazard Identification and Risk Assessment Guide.* Washington, D.C.: U.S. Department of Homeland Security.

Dix, B., Zgoda, B., Vargo, A., Heitsch, S., & Gestwick, T. (2018). *Integrating resilience into the transportation planning process: White paper on literature review findings.* Washington, D.C.: United States Department of Transportation Federal Highway Administration.

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections. (n.d.). Retrieved from https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

Duke University Libraries. (2018). *International Terrorism: Attributes of Terrorist Events (ITERATE)*. Retrieved from https://library.duke.edu/data/sources/iterate

Engineering Safety Consultants. (n.d.). *Quantitative Risk Assessment – QRA*. Retrieved from https://esc.uk.net/quantitative-risk-

Draft - Not for Distribution

assessment/#:~:text=A%20Quantitative%20Risk%20Assessment%20(QRA,company%20assets%20and%20its%20reputation

ESRI. (2021). *Story Map Series Gallery*. Retrieved from https://storymaps-classic.arcgis.com/en/app-list/map-series/gallery-series/#s=30&q=highway

ESRI. (n.d.). *Resilence Dashboard*. Retrieved December 9, 2020, from https://solutions.arcgis.com/emergency-management/help/resilience-dashboard/

FDOT Transportation Asset Management Plan. (2019). Retrieved from https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/planning/performance/fdot-transportation-asset-management-plan_(june-28-2019).pdf?sfvrsn=36c94a6b_2

Federal Highway Administration. (2020, August 28). *State Transportation Innovation Councils*. (United States Department of Transportation) Retrieved February 9, 2021, from https://www.fhwa.dot.gov/innovation/stic/

Federal Rail Administration. (2015). *Risk evaluation framework and selected metrics for tank cars carrying hazardous materials.* Washington, D.C.: U.S. Department of Transportation Federal Railroad Administration.

FEMA. (2017, October). *Hydrologic and Hydraulic (H&H) Study Quick Guide*. (FEMA) Retrieved from https://www.sog.unc.edu/sites/www.sog.unc.edu/files/general_media/FEMA%20HH%20Study%20Quick%20Guide%28Final%29.pdf

FEMA. (2018). *Hazus Flood Model User Guidance.* Washington, D.C.: Federal Emergency Management Agency.

FEMA. (2020). *Hazus Earthquake Model Technical Manual. Hazus 4.2 SP3.* Washington, D.C.: Federal Emergency Management Administration.

FEMA. (2020, July 23). *National Disaster Recovery Framework*. Retrieved from https://www.fema.gov/emergency-managers/national-preparedness/frameworks/recovery

FEMA. (2021, August 6). *National Flood Hazard Layer.* Retrieved from https://www.fema.gov/flood-maps/national-flood-hazard-layer

FEMA Resilience. (n.d.). Retrieved from https://www.fema.gov/about/offices/resilience

Ferguson, W. S. (2002). *Hurricane preparedness and recovery by a transportation agency.* Charlottesville, VA: Virginia Transportation Research Council.

Draft - Not for Distribution

FHWA. (2010). *Advancing Metropolitan Planning for Operations: The Building Blocks of a Model Transportation Plan Incorporating Operations.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration.

FHWA. (2012). *Risk-Based Transportation Asset Management: Achieving Policy Objectives by Managing Risks. Report 3: Risks to Asset Management Policies.* Washington, D.C.: U.S. Department of Transportation Federal Highway Administration. Retrieved from https://www.fhwa.dot.gov/asset/pubs/hif12054.pdf

FHWA. (2013, September 12). *MAP-21 Moving Ahead for Progress in the 21st Century*. Retrieved from https://www.fhwa.dot.gov/map21/factsheets/pm.cfm

FHWA. (2014, December 15). *FHWA Order 5520*. Retrieved from https://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm

FHWA. (2015, March 7). *P3 Project Risk Assessment: P3-VALUE Webinar.* Retrieved from https://www.fhwa.dot.gov/ipd/pdfs/p3/p3-value_2.0_session_4_ra_presentation_030716.pdf

FHWA. (2017, November). *Incorporating Risk Management into Transportation Asset Management Plans.* Retrieved from https://www.fhwa.dot.gov/asset/pubs/incorporating_rm.pdf

FHWA. (2020). *CMIP Climate Data Processing Tool 2.1*. Retrieved from https://fhwaapps.fhwa.dot.gov/cmip

FHWA. (n.d.). *FHWA Sustainability - 2018 - 2020/2024 Pilot Program: Resilience and Durability to Extreme Weather*. Retrieved 01 31, 2021, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/extweatherpilot.cfm

FHWA Funding. (n.d.). Retrieved from https://www.fhwa.dot.gov/specialfunding/er/191011.cfm#_ftn2

FHWA. (n.d.). *Integrating Resilience into the Transportation Planning Process*. Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/planning/

FHWA. (n.d.). *Integrating Resilience into the Transportation Planning Process-White Paper on Literature Review Findings* . Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/planning/integrating_resilience.cfm#toc511390376

FHWA Vulnerability Assessment and Adaptation Framework, 3rd Edition. (n.d.). Retrieved from

Draft - Not for Distribution

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

FHWA, Kalla, H., & Shepherd, G. (n.d.). *Integration of Resilient Infrastructure in the Emergency Relief Program*. Retrieved from https://www.fhwa.dot.gov/specialfunding/er/191011.cfm

Filosa, G., Plovnick, L., Miller, R., & Pickrell, D. (2017). *Vulnerability Assessment and Adaptation Framework- Third Edition.* FHWA. Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf

Fixing America's Surface Transportation Act (FAST Act). (2015). Retrieved from https://www.govinfo.gov/content/pkg/PLAW-114publ94/pdf/PLAW-114publ94.pdf

Flannery, A. (2019, November 13). *Development and incorporation of quantitative risk and resilience analysis standards into agency decision making*. Retrieved from https://trb.secure-platform.com/a/solicitations/15/sessiongallery/197/application/865

Flannery, A., Pena, M. A., & Manns, J. (2018, 1). *Resilience in Transportation Planning, Engineering, Management, Policy, and Administration.* Washington, D.C.: Transportation Research Board. doi:10.17226/25166

Freckleton, D., Heaslip, K., Louisell, W., & Collura, J. (2012). Evaluation of resiliency of transportation networks after disasters. *Transportation Research Record: Journal of the Transportation Research Board, 2284*, 109-116.

Gao, L., Liu, X., Liu, Y., Wang, P., Deng, M., Zhu, Q., & Li, H. (2019). Measuring road network topology vulnerability by Ricci Curvature. *Physica A: Statistical Mechanics and its Applications, 527*.

Gill, J. C., & Malamud, B. D. (2014). Reviewing and Visualizing the Interactions of Natural Hazards. *Reviews of Geophysics, 52*, 680-722.

Girgin, S., Necci, A., & Krausmann, E. (2019). Dealing with cascading multi-hazard risks in national risk assessment: The case of Natech accidents. *International Journal of Disaster Risk Reduction, 35*.

Hammond, P. (n.d.). *Deploying Transportation Resilience Practices in State DOTs.* Retrieved from https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4208

Hampton Roads Transportation Planning District Commission. (2014, February). *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot.* Retrieved from "Assessing

Draft - Not for Distribution

Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure" "Hampton Roads"

Hillsborough County MPO. (2016). *Imagine Hillsborough 2040: Long Range Transportation Plan.* Tampa, FL: Hillsborough County Metropolitan Planning Organization. Retrieved from http://www.planhillsborough.org/wp-content/uploads/2014/10/2040-LRTP-Final-Full-Report-revised-3-28-16-1.pdf

Hodgson, D., McDonald, J. L., & Hosken, D. J. (2015). What do you mean, 'resilient'? *Trends in Ecology & Evolution, 30*(9), 503-506.

Holton, G. A. (2014). *Value-at-risk: Theory and practice. 2nd edition.* Belmont, MA: Glyn A. Holton.

Huq, N., Vosseler, R., & Swimmer, M. (2017). *Cyberattacks Against Intelligent Transportation Systems: Assessing Future Threats to ITS.* Trend Micro.

Husdal, J. (n.d.). *The vulnerability of road networks in a cost-benefit perspective.* Retrieved from https://www.researchgate.net/publication/200113562_The_vulnerability_of_road_networks_in_a_cost-benefit_perspective

ICF International. (2014). *Assessing Criticality in Transportation Adaptation Planning.* Washington, D.C.: U.S Department of Transportation.

INFRARISK. (n.d.). *INFRARISK*. Retrieved 01 31, 2021, from http://www.infrarisk-fp7.eu/the-project-methodology

Institute for Trade and Transportation Studies. (2020). *Freight in the Southeast 10th Conference Trends & Connections: Corridor Planning and Freight Resilience in the Southeast -AASHTO Resilience Connections*. Retrieved from https://web.cvent.com/event/203c14a0-fb45-4518-8eea-da55a344a43d/websitePage:645d57e4-75eb-4769-b2c0-f201a0bfc6ce

International Organization for Standardization (ISO). (2018). *ISO 31000 Risk Management: Guidelines.* Geneva: International Organization for Standarization (ISO).

IPCC. (2007). *AR4 climate change 2007: Synthesis report.* (R. K. Pachauri, & A. Reisinger, Eds.) Geneva, Switzerland: Intergovernmental Panel on Climate Change.

ISO 55001 Asset Management supersedes PAS 55. (n.d.). Retrieved from https://www.bsigroup.com/en-GB/Asset-Management/

Kappes, M. S., Keiler, M., & Glade, T. (2010). From Single- to Multi-Hazard Risk Analysis: A Concept Addressing Emerging Challenges. *Proceedings of the Mountain Risks International Conference.* Firenze, Italy.

Draft - Not for Distribution

KDOT. (2019). *Transportation Asset Management Plan.* Kansas Department of Transportation.

Kreibich, H., & Bubeck, P. (2013). *Natural Hazards: Direct Costs and Losses Due to the Disruption of Production Processes.* New York, NY: UNISDR.

LaFree, G., Smith, B., Freilich, J., Miller, E., Braniff, W., & Smarick, K. (2019, September). *The Terrorism and Extremist Violence in the United States (TEVUS) Database*. (START. National Consortium for the Study of Terrorism and Responses to Terrorism.) Retrieved from https://start.umd.edu/research-projects/terrorism-and-extremist-violence-united-states-tevus-database

Litman, T. (2007, 1). Evaluating rail transit benefits: A comment. *Transport Policy, 14*, 94–97. doi:10.1016/j.tranpol.2006.09.003

Lu, D., Tighe, S., & Xie, W. (n.d.). *Impacts of Flooding on Asphalt Pavements under Climate Change.* Retrieved from https://trid.trb.org/View/1511407

Malet, J.-P., & Remaitre, A. (2015). Probabilistic forecasts of debris-flow hazard at the regional scale with a combination of models. *EGU General Assembly , 17.*

Markolf, S., Hoehne, C., Fraser, A., Chester, M., & Underwood, B. S. (n.d.). *Transportation resilience to climate change and extreme weather events – Beyond risk and robustness.* Retrieved from https://www.sciencedirect.com/science/article/pii/S0967070X17305000

Massachusetts DOT. (n.d.). *Climate Resilience Pilot Project - MassDOT/FHWA*. Retrieved 01 31, 2021, from https://www.mass.gov/doc/massdot-climate-resilience-modeling-overview-faq/download

Mattsson, L.-G., & Jenelius, E. (n.d.). *Vulnerability and resilience of transport systems – A discussion of recent research.* Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0965856415001603

Merrimack Valley MPO. (2015, July). *Merrimack Valley 2016 Regional Transportation Plan*. Retrieved from http://www.miamidadetpo.org/library/plans/2040-long-range-transportation-plan-final-2014-10.pdf

Meyer, V., Becker, N., Markantonis, V., & Schwarze, R. (2012). *Costs of Natural Hazards - A Synthesis.* CONHAZ Consortium.

Miami-Dade MPO. (2014, October). *Miami-Dade 2040 Long Range Transportation Plan*. Retrieved from http://www.miamidadetpo.org/library/plans/2040-long-range-transportation-plan-final-2014-10.pdf

Mid-Region COG. (2015). *Long Range Transportation Plan: Futures 2040 MTP.* Albuquerque, NM: Mid-Region Council of Governments.

Draft - Not for Distribution

Miller, R. (2018). *TAMP: Transportation Asset Management Plan.* Washington State Department of Transportation.

Minnesota DOT. (2022). *Minnesota Go: Planning Minnesota's Transportation Future.* Retrieved from https://www.minnesotago.org/trends

MnDOT. (2018, December). *2017 Minnesota Transportation Resulsts Scorecard.* Retrieved January 29, 2021, from https://www.dot.state.mn.us/measures/pdf/2017%20scorecard%20jg%20SOP.pdf

MnDOT. (2019). *Transportation Asset Management Plan.* Minnesota Department of Transportation.

Moran, M. J., & Monje, C. (2016). *Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analysis - 2016 Adjustment.* Washington, D.C.: U.S. Department of Transportation. Retrieved from https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis

Multi-hazard Loss Estimation Methodology . (n.d.). Retrieved from https://www.fema.gov/sites/default/files/2020-09/fema_hazus_flood-model_technical-manual_2.1.pdf

National Institute of Standards and Technology (NIST). (n.d.). *National Vulnerability Database*. Retrieved from https://nvd.nist.gov/

NCHRP 08-36, Adding Resilience to the Freight System In Statewide and Metropolitan Transportation Plans: Developing a Conceptual Approach. (n.d.). Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP08-36(73)_FR.pdf

NCHRP. (n.d.). *NCHRP Synthesis 527: Resilience in Transportation Planning, Engineering, Management, Policy, and Administration.* Retrieved from http://www.trb.org/Main/Blurbs/177737.aspx

NCHRP Report 931: A Guide to Emergency Management at State Transportation Agencies. (2020). Retrieved from https://www.nap.edu/catalog/25557/a-guide-to-emergency-management-at-state-transportation-agencies

NOAA. (2022, March 15). *NOAA's National Weather Service Storm Prediction Center.* Retrieved from https://www.spc.noaa.gov/gis/svrgis/

Northern Middlesex MPO. (n.d.). *Northern Middlesex Regional Transportation Plan 2016-2040.* Lowell, MA: Northern Middlesex Metropolitan Planning Organization.

Draft - Not for Distribution

O'Har, J. P., Senesi, C., & Molenaar, K. R. (2016, September). *NCHRP 08-36, Task 126: Development of a Risk Register Spreadsheet Tool.* Washington, D.C.: AASHTO. Retrieved from https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3685

Oppikoger, T., Hermanns, R. L., Sandoy, G., & Bohme, M. (2016). Quantification of casualties from potential rock-slope failures in Norway. In *Landslides and Engineered Slopes, Experience, Theory and Practice.* Rome, Italy: Associazione Geotechnica Italiana.

Palm Beach Metropolitan Planning Organization. (2014). *Palm Beach MPO 2040 Long Range Transportation Plan.* Palm Beach Metropolitan Planning Organization. Retrieved from https://www.palmbeachtpa.org/static/sitefiles/LRTP/2040/LRTP.pdf

Parkany, E., & Ogunye, O. (2016). *Transportation Corridor Resilience Assessment.* Charlottesville, VA: University of Virginia, Mid-Atlantic Transportation Sustainability University Transportation Center.

Patrick, J., Senesi, C., & Molenaar, K. R. (2016). *NCHRP 08-36, Task 126: Development of a risk register spreadsheet tool.* Washington, D.C.: Transportation Research Bureau.

Pearson, D., Stein, S., & Jones, J. S. (2000). Risk-based design of bridge scour countermeasures. *Transportation Research Record: Journal of the Transportation Research Bureau, 1696*(1).

PennDOT. (2017). *Phase 1 PennDOT extreme weather vulnerability study report.* Pennsylvania Department of Transportation.

Perona, P., Mischer, A., & Porporato, A. (2009). A Probabilistic Model for Snow Avalanche Occurrence. *EGU General Assembly Conference Abstracts*.

Pescaroli, G., & Alexander, D. (2018). Understanding Compound, Interconnected, Interacting and Cascading Risks: A Holistic Framework. *Risk Analysis, 38*(11), 2245-2257.

Pregnolato, M., Ford, A., M.Wilkinson, S., & J.Dawson, R. (n.d.). *The impact of flooding on road transport: A depth-disruption function.* Retrieved from https://www.sciencedirect.com/science/article/pii/S1361920916308367

Princeton University. (2016). *Chicago Project on Security and Terrorism (CPOST). Suicide Attack Database*. Retrieved from https://cpost.uchicago.edu/about/contact/

Proag, V. (2014). The concept of vulnerability and resilience. *Procedia Economics and Finance, 18*, 369-376.

Draft - Not for Distribution

Proctor, G., Varma, S., & Roorda, J. (n.d.). *NCHRP 08-93, Managing Risk across the Enterprise: A Guide for State Departments of Transportation.* Retrieved from https://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP08-93_FullGuide.pdf

RAND Corporation. (2018, September 11). *RAND Database of Worldwide Terrorism Incidents.* . Retrieved from http://smapp.rand.org/rwtid/search_form.php

Regional Planning Commission. (2015, January). *Metropolitan Transportation Plan: New Orleans Urbanized Area.* Retrieved from http://www.norpc.org/assets/pdf-documents/2044%20NO%20MTP%20FINAL%20ADOPTED.pdf

Resilience. (n.d.). Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/

Risk Management Guidance. (n.d.). Retrieved from https://highways.dot.gov/sites/fhwa.dot.gov/files/docs/federal-lands/construction/15931/risk-management-guidance.pdf

Sanford, W. (2015). *An Overview of ISO 55000 - Standardizing Asset Management.* Retrieved from http://pinnaclereliability.com/wp-content/uploads/2021/01/IJ_Nov-Dec-2015_An-Overview-of-ISO55000.pdf

Serulle, N. U., Heaslip, K., & Brady, B. (2011). A Case Study of Network Transportation Resilience of Santo Domingo, Dominican Republic. *Transportation Research Record: Journal of the Transportation Research Board, 2234*(1).

Smith, B. L., & Damphousse, K. R. (2007, July 30). *American Terrorism Study, 1980-2002 (ICPSR 4639).* Retrieved from https://www.icpsr.umich.edu/web/NACJD/studies/4639

Souppaya, M., & Scarfone, K. (2016). *Guide to Data-Centric System Threat Modeling.* Gaithersburg, MD: National Institute for Standards and Technology.

Southeast Michigan Council of Governments (SEMCOG) and Michigan DOT (MDOT). (2020). *Climate Resiliency and Flooding Mitigation Study.* Climate Resiliency and Flooding Mitigation Study. Retrieved from https://semcog.org/Portals/0/Documents/Plans-For-The-Region/Environment/SEMCOG%20Climate%20Resiliency%20and%20Flooding%20Mitigation%20Study_Report_August%202020.pdf?ver=pjn6fTnLv9BZaM8MuasqVw%3d%3d

Stanujkic, D., & Zavadskas, E. (2015). A Modified Weighted Sum Method Based on the Decision-makeer's Preferred Levels of Performances. *Studies in Informatics and Control, 24*(4).

Draft - Not for Distribution

Stein, S., & Sedmera, K. (2006). *Risk-based Management Guidelines for Scour at Bridges with Unknown Foundations.* Washington, D.C.: Transportation Research Board.

Sullivan, J. L., Novak, D. C., Aultman-Hall, L., & Scott, D. M. (n.d.). *Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach.* Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0965856410000418

Sun, W., Bocchini, P., & Davison, B. D. (2018). Resilience metrics and measurement methods for transportation infrastructure: the state of the art. *Sustainable and Resilient Infrastructure, 5*, 168-199.

Ta, C., Goodchild, A. V., & Pitera, K. (2009, 1). Structuring a Definition of Resilience for the Freight Transportation System. *Transportation Research Record: Journal of the Transportation Research Board, 2097*, 19–25. doi:10.3141/2097-03

The Moving Ahead for Progress in the 21st Century Act (MAP-21). (n.d.). Retrieved from https://www.govinfo.gov/content/pkg/BILLS-112hr4348enr/pdf/BILLS-112hr4348enr.pdf

The National Academies of Sciences, Engineering, and Medicine. (2020). *Asset management approaches to identifying and evaluating assets damaged due to emergencies.* Washington, D.C.: The National Academies Press.

The National Academy of Sciences, Enegineering and Medicine. (n.d.). *Transportation Resilience Metrics*. Retrieved February 2021, from https://www.nationalacademies.org/our-work/transportation-resilience-metrics#sectionProjectScope

Tri-County Regional Planning Commission. (2015). *Envision HOI: Heart of Illinois Long Range Transportation Plan.* Peoria, IL: Tri-County Regional Planning Commission.

Turner, D. (2015). *Fragility Assessment of Bridge Superstructures Under Hydrodynamic Forces.* Retrieved from https://mountainscholar.org/bitstream/handle/10217/170400/Turner_colostate_0053N_13377.pdf?sequence=1

UDOT. (2019). *Utah Transportation Asset Management Plan.* Salt Lake City, UT: State of Utah.

UN/ISDR. (2004). *Living with risk: a global review of disaster reduction initiatives.* Geneva: UN Publications.

University of Maryland. (2020). *Global Terrorism Database*. Retrieved from https://start.umd.edu/gtd/

Draft - Not for Distribution

US DOT. (D.C.). *FY-2015 Annual Performance Report / FY-2017 Annual Performance Plan.* Washington, D.c.: U.S. Department of Transportation.

USACE. (2017, July 18). *Sea-Level Change Curve Calculator (Version 2019.21)*. Retrieved from https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html

USACE. (n.d.). *HEC-RAS.* Retrieved from https://www.hec.usace.army.mil/software/hec-ras/

USACE. (n.d.). *Public Tools Developed by USACE--Climate Impacted Hydrology*. Retrieved from https://www.usace.army.mil/corpsclimate/Public_Tools_Dev_by_USACE/Climate-Impacted_Hydrology.aspx

USACE. (n.d.). *Sea Level Tracker*. Retrieved from https://climate.sec.usace.army.mil/slr_app/

USGAO. (2020, August 5). *A Climate Migration Pilot Program Could Enhance the Nation's Resilience and Reduce Federal Fiscal Exposure.* Retrieved from https://www.gao.gov/products/gao-20-488

USGS. (1971, February 9). *CISN Rapid Instrumental Intensity Map for San Fernando Earthquake*. Retrieved from https://www.cisn.org/shakemap/sc/shake/San_Fernando/intensity.html

USGS. (n.d.). *Landslide Inventory.* Retrieved from https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=ae120962f459434b8c904b456c82669d

USGS. (n.d.). *Peak Streamlfow for the Nation*. Retrieved August 12, 2020, from https://nwis.waterdata.usgs.gov/usa/nwis/peak

VizSec Organization. (n.d.). *VIZSEC*. Retrieved from https://vizsec.org/data/

Volpe. (2013, September 17). *Infrastructure Resiliency: A risk-based Framework.* Retrieved January 15, 2020, from https://www.volpe.dot.gov/sites/volpe.dot.gov/files/docs/Infrastructure%20Resiliency_A%20Risk-Based%20Framework.pdf

VTRANS. (2019). *User Guide for the Vermont Transportation Resilience Planning Tool (TRPT).* State of Vermont. Retrieved from https://vtrans.vermont.gov/sites/aot/files/planning/documents/planning/TRPT%20User%20Guide%201.0.pdf

VTRANS. (n.d.). *Transportation Resilience {Planning Tool)*. Retrieved 01 31, 2021, from https://vtrans.vermont.gov/planning/transportation-resilience

Draft - Not for Distribution

Weilant, S., Strong, A., & Miller, B. (2019). *Incorporating resilience into Transportation Planning and Assessment.* RAND Corporation.

Weilant, S., Strong, A., & Miller, B. (2019). *Incorporating Resilience into Transportation Planning and Assessment.* Santa Monica, CA: RAND Corporation. Retrieved from https://www.rand.org/content/dam/rand/pubs/research_reports/RR3000/RR3038/RAND_RR3038.pdf

Werner, S., Taylor, C. E., Cho, S., Lavoie, J.-P., Hyuck, C., Eitzel, C., . . . Eguchi, R. T. (2006). *REDARS 2 Methodology and Software for Seismic Risk Analysis of Highway Systems.* United States Department of Transportation Federal Highway Administration.

Westen, C. v., Kingma, N., Damen, M., Kerle, N., & Alkema, D. (2011). *Multi-hazard risk assessment distance education course guide book.* Twente, Netherlands: University of Twente.

WHO. (2009). Qualitative Risk Characterization in Risk Assessment. In *Risk characterization of microbiological hazards in food: Guidelines Vol. 17.* World Health Organization.

Winter, M. G., Smith, J. T., Fotopoulou, S., Pitilakis, K., Mavrouli, O., Corominas, J., & Argyroudis, S. (2014). An Expert Judgement Approach to Determining The Physical Vulnerability of Roads to Debris Flow. *Bulletin of Engineering Geology and the Environment, 73*(2), 291-305.

WSDOT. (2011, November). *Climate Impacts Vulnerability Assessment.* Retrieved from https://wsdot.wa.gov/sites/default/files/2017/11/15/ENV-Climate-VulnerabilityAssessment.pdf

WSP. (n.d.). *Resiliency Case Studies: State DOT Lessons Learned.* Retrieved from https://environment.transportation.org/pdf/rsts/aashto_resiliency%20_case_studies.pdf

WV DOT Transportation Asset Management Plan. (2019). Retrieved from https://transportation.wv.gov/highways/programplanning/Documents/2019-Final-TAMP.pdf

Wylie, D. C. (2015). *Rock Fall Engineering.* Boca Raton, FL: CRC Press.

Zapata, C., & Houston, W. (2008). *NCHRP 602, Calibration and Validation of the Enhanced Integrated Climatic Model for Pavement Design.* Retrieved from https://www.nap.edu/catalog/23098/calibration-and-validation-of-the-enhanced-integrated-climatic-model-for-pavement-design

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APPENDIX C – GAP ASSESSMENT

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NCHRP PROJECT 23-09

SCOPING STUDY TO DEVELOP THE BASIS FOR A HIGHWAY STANDARD TO CONDUCT AN ALL-HAZARDS RISK AND RESILIENCE ANALYSIS

TASK 1.C DELIVERABLE – GAP ASSESSMENT OF THE STATE OF PRACTICE

Prepared by

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Jacobs Engineering Group

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March 3, 2021

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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1 Introduction

Research to date suggests state DOTs and other transportation agencies currently employ different methods to incorporate risk and resilience analyses in their planning processes. These differences include an assortment of data sources, a variety of different methodologies, with results that can be difficult to compare with each other. Identifying the gaps in these differing practices is an important step in producing a standard framework for risk and resilience analysis for assessing highway infrastructure. Developing a standard framework establishes a common methodology to produce results that could be compared across agencies and jurisdictions and allow apples-to-apples comparisons of risk and resilience practices and outputs. Identifying the gaps that exist is the first step in standardizing the way these analyses are conducted.

1.1 Purpose

This project seeks to (1) develop a comprehensive and consistent set of risk and resilience related terminology and (2) formulate a research roadmap to establish a framework that supports quantitative assessments of all-hazard risk and resilience for State and local departments of transportation (DOTs). These objectives will be met by conducting four tasks, the first of which includes three activities –develop a risk and resilience glossary of terms, prepare a state of practice review, and conduct a gap assessment. This report is the third of the three Task 1 activities.

This document was prepared from the results of the Literature Review and reviews the gaps that may exist in the state of practice of how DOTs conduct quantitative all-hazard risk and resilience assessments.

1.1.1 Methodology

The methodology for this gap analysis started with the barriers and limitations that were noted in the state of practice report. That information was reviewed in detail, including the limitations and lessons learned. Potential gaps were compiled and organized into three categories:

1. *Processes*, including institutional and DOT business processes that are used to develop risk and resilience assessments.
2. *Technologies and Tools*, which are used to develop and support assessments.
3. *Technical Capacity Building*, including gaps in areas such as educational support, staff training, and skill development.

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1.1.2 Gap Analysis Framework

The gap analysis was organized around each of the three categories listed in Section 1.1.1. including:

- Processes
- Technologies and tools
- Technical capacity building

2 Gaps in Processes

The first set of gaps relate to the business processes for State DOTs, Emergency Management Agencies (EMAs) and other partner organizations. Various methods and frameworks have been adopted and implemented used to conduct risk and resilience assessments with varying levels of analytical or evaluation effort covering both qualitative and quantitative approaches. The gaps listed below are those that have been identified from the processes thus far implemented in the existing state of practice.

Gap 1: Risk and Resilience Assessment Support to Interagency Planning for Disasters

Current State: State DOTs collaborate with State emergency management agencies (EMAs) and other state agencies before, during, and after disasters. Phases include preparedness, response, recovery, and mitigation. Inter-agency collaboration between DOTs and EMAs usually occurs most during the response and recovery phases since emergency managers rely on DOT to operate traffic control centers to monitor evacuation and recovery traffic, control dynamic message signs, and set up detours as needed. Recovery and detour management plans do not always take into consideration highway network performance in their decision-making framework.

Gap identified: There are opportunities to incorporate elements of risk and resilience in the mitigation and preparedness phases to mitigate future impacts and plan for future disasters. Risk and resilience outputs that provide a comparative and compounding consequence and risk analysis of scenarios of critical asset failures are not available to support emergency management and recovery operations. There are no widely applied methodologies to prioritize asset repair and restoration plans to minimize the impacts of disruptions that have system-wide impacts.

Desired State	Action Item

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• Planning for hazard recovery and mitigating hazard impacts become routine and are incorporated with asset and performance management plans	• Incorporate in the standard how results of risk and resilience analysis should inform recovery and preparedness strategies. • Incorporate threats and hazards from hazard mitigation plans into asset, performance management and long-range transportation plans

Gap 2: Define and Adopt Risk and Resilience Performance Measures

Current State: There are a limited number of MPOs or DOTs that currently incorporate risk and resilience into performance measures to make investment and policy decisions to achieve their performance goals. Currently, about 10 percent of State DOTs and 25 percent of MPOs incorporate risk and resilience into planning and other DOT business processes.

Gap identified: Currently there is no standard set of performance measures to use when evaluating the risk to highway transportation system or specific assets and their resilience.

Desired State	Action Item
• Widespread use of performance measures in transportation plans like TAMPs	• Prioritize existing performance measures for incorporation in the standard. • Identify risk and resilience performance metrics that advance and align with the MAP-21 planning factors.

Gap 3: Monitoring Results of Risk and Resilience Assessments and their Integration into DOT Decision-making

Current State: Many state DOTs have conducted risk and resilience assessments to identify system and asset vulnerabilities with varying degrees of integration into agency processes to monitor the impacts of implementing resilience strategies and plans for improved risk management.

Gap identified: Performance-based plans lack risk and resilience measures that monitor implementation of adaptation strategies, resilient investments, and the results of effective planning for risk mitigation.

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Desired State	Action Item
• Develop tools and metrics to evaluate the progress and implementation of integrating risk and resilience assessments into DOT's processes.	• Establishing monitoring and evaluation plan to evaluate performance with agency objectives. • Assess suitability of data and key performance indicators to support periodical evaluations against plans.

Gap 4: Scoping Guidance for Risk and Resilience Analysis

Current State: During the scoping process, planners identify the stressors, threats and hazards potentially impacting highway assets. One of the key decision points of a risk and resilience assessment is deciding which threat-asset pairs should be included (or screened out) as part of scoping exercise (see Figure 1). This is typically done qualitatively using practitioner judgment and consensus.

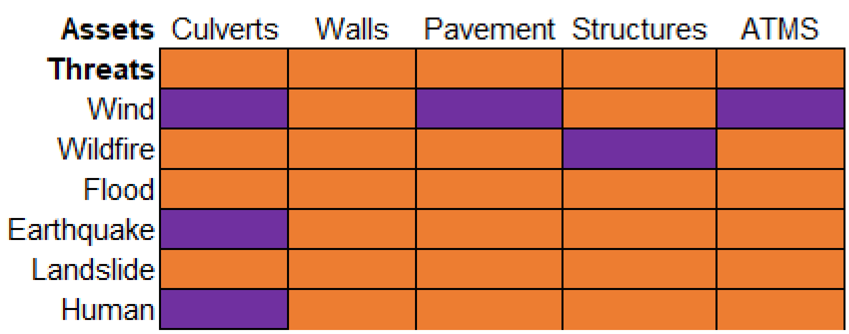

Figure 1: Sample Table of Threat-Asset Pairs

To manage the scope of the assessment, practitioners screen out hazards based on knowledge of which hazards are unlikely or based on other resources such as state hazard mitigation plans (developed by EMAs) that identify threats and hazards and that are often incorporated into DOT emergency operations plans.

Gaps identified: State DOTs do not have guiding principles to support managing the scope for risk and resilience analyses at the system, corridor, or regional level, without inadvertently screening out any consequential as a result of subjective judgments. Furthermore, not all state DOTs refer to EMA hazard mitigation plans. There are

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opportunities for more collaboration between DOTs and EMAs in threat and hazard identification and in developing risk assessments.

Desired State	Action Item
• DOTs identify the spectrum of stressors, threats, and hazards that are most consequential based on observed trends	• Identify and characterize all pairs of hazards and assets and develop criteria for screening out pairs during scoping. • Conduct workshops and stakeholder outreach to improve collaboration between DOTs and EMAs during the planning, mitigation, and preparedness phases. • DOTs collaborate with EMAs for Statewide Hazard Mitigation Plan updates.

3 Gaps in Technologies and Tools

The second set of gaps relate to the technologies and tools that are used to support risk and resilience assessments. As listed in the literature review, there are a variety of technologies and tools that are available to planners. These include:

- Qualitative, semiquantitative and quantitative risk assessment tools
- Asset vulnerability estimation tools and
- Criticality and communication tools

These tools have limitations and gaps in their underlying methodologies as well as data requirements necessary for their use. This section summarizes those gaps.

Gap 5: Choice of Methodology for Risk Assessment Tools

Current state: There are three broad categories of tools that agencies use to catalogue and estimate the magnitude of specific risks:

- <u>Qualitative Tools</u> such as risk registers or risk heat maps where planners identify threats and estimate probabilities and consequences based on expert judgement.
- <u>Deterministic Quantitative Risk Models</u>, such as Risk Analysis and Management for Critical Asset Protection (RAMCAP Plus ^{SM}), that employ and produce single values as inputs and outputs.

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- Probabilistic Models, such as the Mechanistic Empirical Pavement Design Guide (MEPDG), that incorporate the uncertainty of natural phenomena in their inputs and produce a range of values as outputs.

Gaps identified: the variety of methodologies used to catalogue risks makes it difficult to compare risks consistently and may not be useful for regional and national evaluation for potential federal aid or other funding programs. Additionally, more sophisticated methodologies, such as probabilistic models, provide more information to planners but come at a cost of greater effort and understanding and communicating their results to decision-makers and the public. Finally, the different methodologies are mostly used for planning-level tools, and there are gaps in how these methodologies can be incorporated into operational tools. This would mean that, for example, information collected, and plans made related to certain assets would be made readily available to responders in the event of a disaster that impacted those assets.

Desired State	Action Item
• The highway standard uses a consistent model and methodology for risk assessments that produces results that can be compared across jurisdictions. • Model results can be used to inform both nationwide investment decisions related to risk and resilience and operational issues.	• Engage stakeholders in workshops to survey their experience with risk assessment tools and determine if it is possible to pursue a consensus methodology. • Use the roadmap to chart a path toward a consensus risk assessment methodology, including data requirements and steps to tool implementation.

Gap 6: Data Availability and Suitability for Risk and Resilience Assessments

Current State: For the purposes of this effort, data needs for highway risk and resilience assessments can be separated into two broad categories:

- Highway asset and topographical data
- Historical and projected hazard/stressor data

State DOTs maintain a wide range of asset data that include location, condition, and other descriptive elements that are critical in supporting risk and resilience assessments. There are standardized datasets such as Highway Performance Monitoring System (HPMS) and the National Bridge Inventory (NBI) data, that are submitted by the states to Federal Highway Administration (FHWA). The states also maintain large amounts of other non-standardized data relevant to their state and covering the state and local

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systems and assets using their own asset management and recordkeeping systems. Hazard data is maintained by a variety of organizations.

Gaps Identified: The variety and dispersion of data sources, especially those relevant to hazards, makes it incumbent on planners to compile data sources, adding to effort to conducting risk and resilience assessments. Additionally, data maintained by state DOTs for certain assets, such as culverts and roads outside of major systems like the National Highway System, can be missing key attributes.

Desired State	Action Item
• Hazard data is accessible to planners in a format that is routinely updated and requires low effort to obtain and use • State DOTs coordinate with state EMAs, state climate office, or other Federal and state partners who maintain and manage stressor data for risk and resilience analyses, whether in standardized or non-standardized datasets.	• Review hazard data sources and survey stakeholder experience with those sources to curate options for hazard data. • Identify list of key attributes and data points in DOT asset data that are essential to conducting risk and resilience analyses and document update responsibilities, cycles, and maintain necessary metadata.

Gap 7: Develop Standard Consequence Estimation Methodologies

Current State: Consequence analysis estimates are used in risk management processes to estimate the monetary value of the cost incurred when an asset is disrupted, damaged or destroyed. Currently, there is no widely adopted methodology for estimating consequences of disruptions, loss or damage on highway assets. The exception is the flood model for bridges through HAZUS-MH, a GIS tool provided by FEMA.

Identified Gaps: Consequence estimation methodologies should be developed for highway assets that contain appropriate guidance related to metrics of asset criticality, such as traffic volume. These methodologies need to distinguish between consequences to asset managers and users of the asset for planning and policy purposes.

Desired State	Action Item
• A consistent framework and toolkit to estimate consequence and/or loss of assets for a range of asset categories and configurations (functional class, etc.).	• Work with FEMA (and coordinate with USACE) to expand HAZUS's lifeline systems to include more highway assets and threat pairs. • Develop exposure-damage functions (similar to the depth-damage curves

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	for flood) for highway assets and provide guidance on context-based application (on applicability and transferability).

4 Gaps in Technical Capacity Building

The final set of gaps relate to the technical capacity that agencies have to carry out risk and resilience assessments. As risk and resilience methodologies become more sophisticated, they require more staff training and additional skill development to conduct the assessments on a regular basis and within constrained resources. The gaps catalogued here document the challenges that agencies face in building capacity to handle increasing technical demands.

Gap 8: Training Material Available for DOT Staff for Risk and Resilience Assessments

Current State: There many training materials available for risk and resilience assessments from current research and multiple federal agencies. First, there are a series of research guidebooks published by the NCHRP, including:

- NCHRP 08-93, Managing Risk Across the Enterprise: A Guide for State Departments of Transportation
- NCHRP 08-36, Development of a Risk Register Spreadsheet Tool
- NCHRP 602, Calibration and Validation of the Enhanced Integrated Climatic Model for Pavement Design
- NCHRP Synthesis 527, Resilience in Transportation Planning, Engineering, Management, Policy, and Administration
- NCHRP 08-113, Integrating Effective Transportation Performance, Risk, and Asset Management Practices
- NCHRP 08-36, Adding Resilience to the Freight System in Statewide and Metropolitan Transportation Plans: Developing a Conceptual Approach
- NCHRP 20-117, Deploying Transportation Resilience Practices in State DOTs

Second, the FHWA maintains recorded webinars on resilience topics specific to transportation and highways.[1] Finally, FEMA also has numerous webinars that relate to preparedness topics[2] as well as building resilient infrastructure.[3]

Identified Gaps: Though there are many training materials available for risk and resilience analyses, they are not standardized in a way that leads to consistent usage. A standard to conduct an all-hazards risk and resilience analysis must also come with training modules and other materials so it can be implemented consistently across jurisdictions and transportation disciplines.

Desired State	Action Item
• The standard to conduct an all-hazards risk and resilience analysis is accompanied by training materials or modules, similar to the FHWA Vulnerability Assessment and Adaptation Framework tool or RAMCAP Plus ^{SM}.	• Develop a National Highway Institute course for education and professional development to support and implement highway risk and resilience assessments. • Develop professional development training material in the topic areas covering risk, resilience, and process for conducting risk and resilience assessments. • Conduct Risk and Resilience Webinars

Gap 9: Variety of Definitions and Frameworks for Risk and Resilience Analyses

Current State: There are numerous definitions used for terms related to risk and resilience. In addition, a variety of frameworks for understanding risk and resilience assessments have been also identified. Finally, there are differing opinions on the threats and hazards facing a transportation system, with disagreement over what constitutes a “threat” or a “hazard” and differing lists of both.

Gaps Identified: The variety of definitions causes confusion among practitioners as well as misunderstandings of the concepts and goals of risk and resilience analyses. This can prevent the adoption of these analyses as part of the regular planning process and their incorporation with other plans.

[1] https://www.fhwa.dot.gov/environment/sustainability/resilience/webinars/index.cfm
[2] https://www.fema.gov/emergency-managers/individuals-communities/preparedness-webinars
[3] https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities/july-2020-sessions

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Desired State	Action Item
• Existence of an authoritative source of risk and resilience definitions that planners and practitioners across transportation disciplines can rely on.	• Include agreement on definitions as an agenda item during stakeholder engagement • Building on the glossary of terms created for this project, publish a glossary of terms and key concepts with the highway standard for risk and resilience analyses.

Gap 10: Many Risk and Resilience Tools Do Not Meet Accessibility Principles and Standards

Current State: A variety of tools have been created to aid in conducting risk and resilience assessments. These tools meet varying degrees of accessibility compliance, where some tools are accessible for all users and other tools are limited in their choice of color, use of alt-text, and other features.

Gaps Identified: Tools that may be necessary for planners to use in a risk and resilience standard should be developed to accessibility standards so that they are accessible for all users. In particular, these tools should incorporate color access while visualizing risk (avoid using red-green palettes for example).

Desired State	Action Item
• Standard tools that need to be used to conduct risk and resilience analyses are accessible to all users.	• Review existing tools through the lens of accessibility and highlight potential issues and their solutions. • Require the use of accessible color palettes.

5 Conclusion

This document describes selected gaps that exist in the state of practice of how state DOTs conduct quantitative all-hazard risk and resilience assessments. Gaps were organized into three categories, (1) Processes, including institutional processes that are used to develop risk and resilience assessments, (2) Technologies and Tools, which are used to develop and support assessments and (3) Technical Capacity Building, including gaps in areas such as staff training and skill development. From the Gap Analysis, several key themes emerged.

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- State DOTs do not have a consistent way of determining the scope and applicable hazards for risk and resilience analyses, whether at the system, corridor, or regional level. As a result, there are opportunities for more collaboration between DOTs and EMAs in threat and hazard identification and in developing risk assessments.
- To date, a limited number of MPOs or DOTs incorporate risk and resilience into performance measures. In addition, there is currently no standard process or performance measure to use when evaluating highway transportation assets.
- The variety of methodologies used to catalogue risks makes it difficult to compare risks across different jurisdictions. Similarly, the variety and dispersion of data sources, especially those relevant to hazards, makes it incumbent on planners to compile data from multiple sources, adding to effort to conducting risk and resilience assessments.
- Though there are many training materials available for risk and resilience analyses, there is no standardization that would enable more consistent usage across multiple agencies.
- A consistent theme in the literature review findings was the multitude of differing resilience terms. The variety of definitions cause confusion among practitioners as well as misunderstandings of the concepts and goals of risk and resilience analyses. Therefore, the glossary of terms under development as part of this project will be an important contribution to the research.

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APPENDIX D – RESEARCH PROBLEM STATEMENTS

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TASK 3: DESIGN RESEARCH ROADMAP AND DEVELOP RESEARCH PROBLEM STATEMENTS

NCHRP PROJECT 23-09

SCOPING STUDY TO DEVELOP THE BASIS FOR A HIGHWAY STANDARD TO CONDUCT AN ALL-HAZARDS RISK AND RESILIENCE ANALYSIS

TASK 3C DELIVERABLE – DEVELOP RESEARCH PROBLEM STATEMENTS

Prepared by

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November 29, 2021

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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Introduction and Background

Under the auspices of NCHRP 23-09, "Scoping Study to Develop the Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis" the research team conducted an extensive literature review, gap assessment and stakeholder engagement to solicit feedback in support of the development of the Highway R&R Manual Research Roadmap:

- Literature Review and Gap Assessment – February 17, 2021
- Stakeholder engagements – March/April 2021 and September 22, 2021

A research roadmap is a high-level document that guides the development of a research program by (1) identifying the gaps that need to be addressed, (2) defining the research questions that will satisfy the gaps, and (3) developing the timeline for investigating the research questions. The following sections describe the methodology the research team employed for developing the roadmap and Research Problem Statements (RPSs).

Objective

The objective of the Highway R&R Manual Research Roadmap is to provide long-term guidance on future research and development activities for the purpose of developing a framework for a quantitative, all-hazards risk and resilience assessment program.

Methodology

Based on the Literature Review and Gap Assessment conducted in Task 2 the research team identified knowledge gaps that can be classified into three thematic lanes:

- Organizational development, Outreach, and Implementation
- Risk and Resilience Assessment Processes
- Technology and Tools

The research team compiled feedback from stakeholder engagements to develop 12 draft Research Problem Statements (RPSs) and two research roadmap options. The two options were presented at the September 2021 virtual workshop.

Workshops

The stakeholder engagements gathered feedback from a variety of transportation professionals familiar with R&R concepts to aid the research team define the content and prioritization of future research in pursuit of a research roadmap to advance the practice of R&R assessment in State Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs). The research team presented two research roadmap options with the corresponding RPSs to stakeholders from US DOT, FHWA, and academia during the September workshop for discussion and feedback. As

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part of the workshop, the attendees participated on an interactive session where each participant was be able to provide editorial input to the provided RPSs as well brainstorm topics by thematic lane and map those topics with the existing RPSs. Based on the feedback obtained during the workshop the research team reviewed the original set of RPSs to incorporate the participant feedback. Since all the topics provided during this activity were match with an existing RPS, there was no need to create new RPSs. *Figure 1* shows a screenshot of the interactive Mural activity.

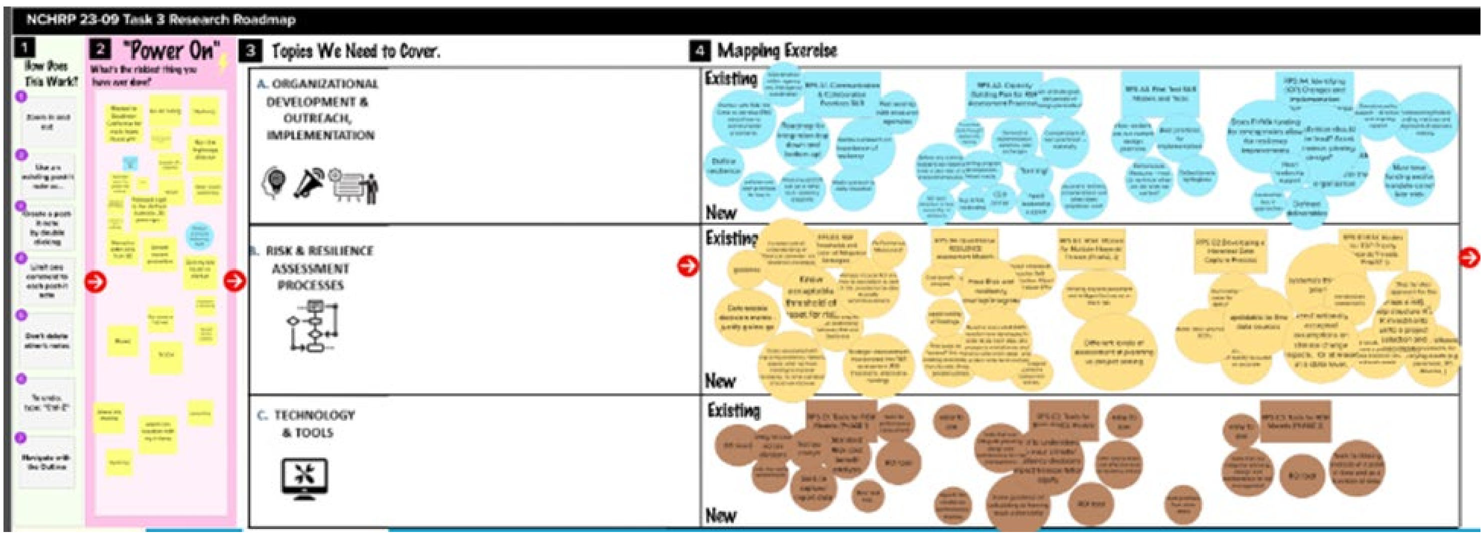

Figure 1. Research Problem Statements Topics and Mapping Exercise

Final Roadmap Overview

The outcome of the NCHRP 23-09 project was utilized for the development of a Research Needs Statement (RNS) for consideration by the TRB Committee on Transportation Asset Management (AJE30) to be submitted for the NCHRP's research AJE30, the AASHTO liaison for this project and the panel chair, the original Roadmap proposed by the research team was revised to accommodate a 7-year Roadmap divided in 3 distinct phases with particular products for each phase. **Phase 1** focuses on development of assessment methodologies and the Highway R&R Manual. **Phase 2** focuses on testing the manual and developing agency capacity building to facilitate implementation of R&R-focused initiatives. **Phase 3** accommodates the development of tools and a revision of the final Highway R&R Manual and capacity building. The revised Roadmap was discussed and approved by the Research Panel during a panel meeting on October 6th. The final roadmap with corresponding RPSs is shown in *Figure 2*.

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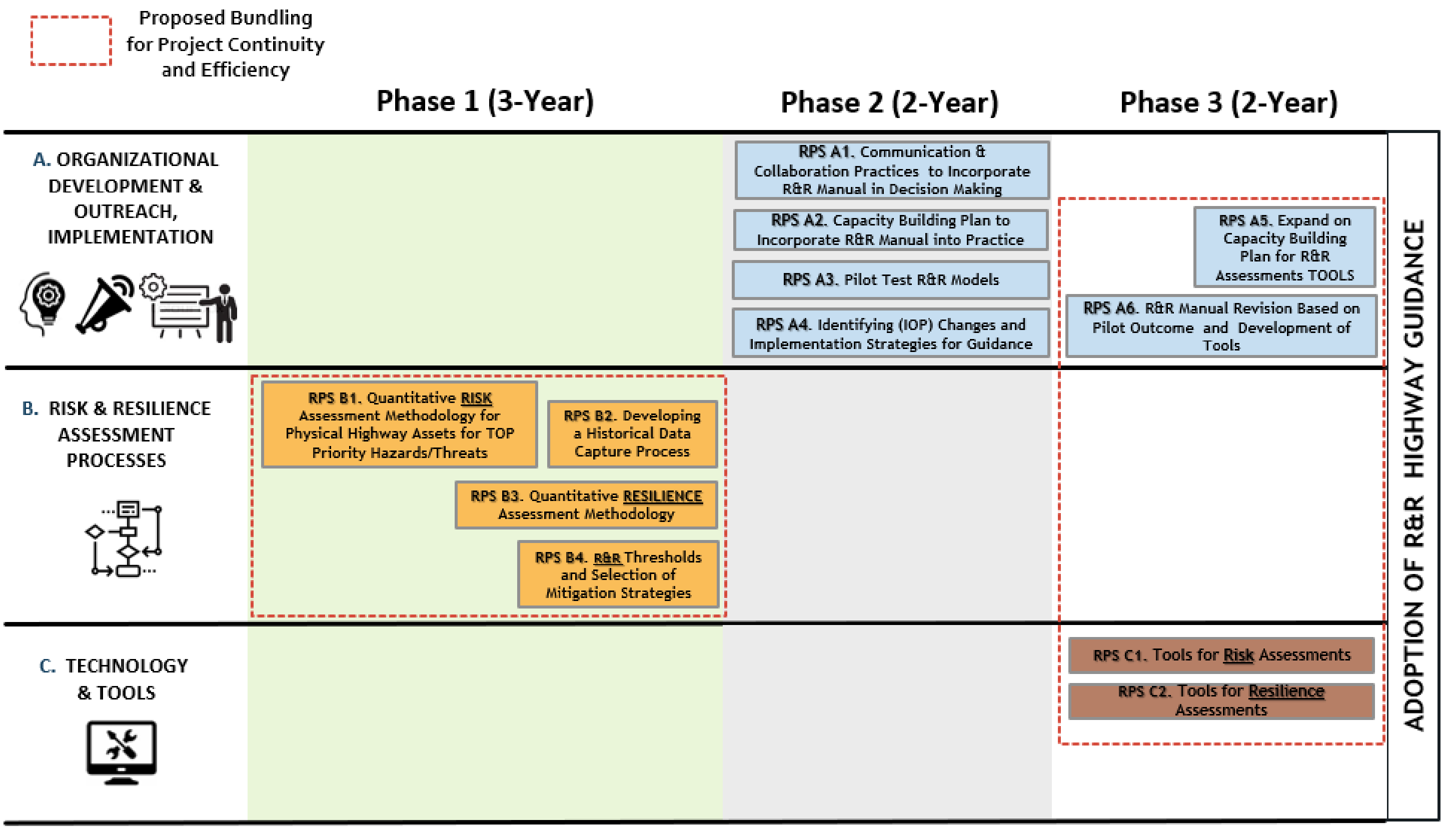

Figure 2. Final Research Roadmap

The dashed red boxes in *Figure 2* suggest opportunities to bundle selected projects to enhance project continuity and efficiency, i.e., Phase 1 and Phase 3 projects can potentially be bundled into single projects as shown in the figure.

Research Problem Statements Overview – By Thematic Lane

The proposed research problem statements (RPSs) for each Key Knowledge Gap/Thematic Lane for NCHRP 23-09 are listed by thematic lane in *Figure 3*.

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Organizational Development & Outreach, Implementation	Risk & Resilience Assessment Process	Technology & Tools	Knowledge Gaps	Highway R&R Manual Research Roadmap RPS
●			**A1.** Creating Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management.	
●			**A2.** Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency (R&R) Assessments at Transportation Agencies.	
●			**A3**. Pilot Testing the Highway Risk and Resilience (R&R) Manual and Interface with Existing Asset Management Systems and Other Agency Functions	
●			**A4**. Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of the Highway R&R Manual.	
●			**A5.** Enhancing the Capacity Building and Implementation Plans to Incorporate Highway Risk and Resilience Manual and Tools	
●			**A6.** Revising the Highway Risk and Resilience Manual	
	●		**B1.** Establishing a Quantitative Multi-hazard **Risk** Assessment Methodology for Highway Assets	
	●		**B2.** Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments.	
	●		**B3.** Establishing a Quantitative **Resilience** Assessment Methodology for Transportation Highway Assets	
	●		**B4.** Establishing Considerations for Defining Risk and Resilience Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure	
		●	**C1.** Identifying and Developing Analytical Tools to Conduct **Risk** Assessments for Highway Assets.	
		●	**C2.** Identifying and Developing Analytical Tools to Conduct **Resilience** Assessments for Highway Assets.	

Figure 3. Highway R&R Manual Research Roadmap Potential Projects

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Research Problem Statements – By Roadmap Phase

The proposed research problem statements (RPSs) for each phase of the Roadmap are:

Phase 1 - Development of "Highway Risk & Resilience Manual"

- RPS B1. Establishing a Quantitative Multi-hazard **Risk** Assessment Methodology for Highway Assets
- RPS B2. Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments.
- RPS B3. Establishing a Quantitative **Resilience** Assessment Methodology for Transportation Highway Assets
- RPS B4. Establishing Considerations for Defining Risk and Resilience (R&R) Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure

Phase 2 - Pilot testing and implementation of "Highway Risk & Resilience (R&R) Manual"

- RPS A1. Creating Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management.
- RPS A2. Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency Assessments (R&R) at Transportation Agencies.
- RPS A3. Pilot Testing Highway Risk and Resilience Assessment (R&R) Manual and Interface with Existing Asset Management Systems and Other Agency Functions
- RPS A4. Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of the Highway Risk and Resilience (R&R) Manual.

Phase 3 - Development of tools and revision of "Highway Risk & Resilience (R&R) Manual"

- RPS A5. Enhancing the Capacity Building and Implementation Plans to Incorporate Highway Risk and Resilience (R&R) Manual and Tools
- RPS A6. Revising Highway Risk and Resilience (R&R) Manual
- RPS C1. Identifying and Developing Analytical Tools to Conduct **Risk** Assessments for Highway Assets.
- RPS C2. Identifying and Developing Analytical Tools to Conduct **Resilience** Assessments for Highway Assets.

Formal RPSs for each phase are presented below.

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Phase 1 - Development of "Highway Risk & Resilience Manual"

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1. PROBLEM TITLE (RPS B1)
Establishing a Quantitative Multi-hazard Risk Assessment Methodology for Highway Assets

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH

MAP-21 and FAST legislation have compelled transportation agencies to incorporate risk assessment into their Transportation Asset Management Plans (TAMPs). Moreover, the passage of the Infrastructure Investment and Jobs Act (IIJA) requires the USDOT to establish an intergovernmental risk and system resilience assessment process. However, the risk assessment methodologies most employed in the past tended to rely on qualitative methods, such as risk registers and heat maps. Unfortunately, qualitative methods do not support economic analysis of alternative adaptation strategies and, therefore, are inadequate for asset or project-level analysis, or any situation where economic analysis is required. Some transportation agencies have started to develop their own risk assessment methodologies and processes, but the state of practice varies on the maturity of development and incorporation of these processes. State DOTs and Metropolitan Planning Organizations (MPOs) have highlighted the need for better and standardized processes that help them conduct a risk assessment of their assets and networks. This research will cover the top priority threats/hazards and highway assets identified in previous studies.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of risk and resilience have been conducted through the NCHRP Process as well as FHWA. Below is a short list of some of the more relevant NCHRP projects that address collaboration and communications strategies within the transportation sector:

- NCHRP 08-118, Risk Assessment Techniques for Transportation Asset Management
- NCHRP 20-125, Strategies for Incorporating Resilience into Transportation Networks
- NCHRP 15-61. Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure
- NCHRP 24-25, Guidelines for Risk-Based Management of Bridges with Unknown Foundations
- NCHRP 15-80, Design Guide and Standards for Infrastructure Resilience
- NCHRP 20-06, Topic 25-03 Managing Enhanced Risk in the 'Mega Project' Era
- NCHRP Synthesis 494, Life-Cycle Cost Analysis for Management of Highway Assets
- NCHRP 20-59(51)C, Security 101: A Physical & Cyber Security Primer for Transportation Agencies
- NCHRP 8-70, NCHRP Report 706: Uses of Risk Management and Data Management to Support Target-Setting for Performance-Based Resource Allocation by Transportation Agencies
- NCHRP 12-43, NCHRP Report 483: Bridge Life Cycle Cost Analysis
- NCHRP 20-24(74), Executive Strategies for Risk Management by State Departments of Transportation
- NCHRP 20-59(56), Support for State DOT Transportation Systems Resilience and All-Hazards Programs
- NCHRP 15-61/61A, Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure

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4. RESEARCH OBJECTIVE

The objective of this research is to supplement current and past efforts of NCHRP projects and state of practice among transportation agencies to develop quantitative, repeatable methodologies for conducting quantitative risk assessments for top priority threats/hazards for highway assets identified in previous work. Utilizing the conceptual framework for R&R assessment for highway assets developed in NCHRP 23-09 this research will:

- Assess the current state of practice on the process and incorporation of risk assessments for highway assets through literature review, stakeholder interviews and a national survey. Sate of practice should include R&R models, metrics, tools, etc.
- Apply the conceptual framework for risk assessment for highway assets to create a guidance document to help transportation agencies to quantitatively conduct risk assessments to highway assets.
- Develop a risk assessment purpose and need matrix that maps the existing use of R&R assessment efforts to the intended purpose and address success, challenges and needs.
- Identify existing criticality assessment criteria, methodologies and metrics for highway assets/networks that can be used on the development of the Highway R&R Manual.
- Identify data needs and sources.
- Identify and develop methodologies for identification and threat/hazard characterization including thread thresholds/severity.
- Identify and develop methodologies for vulnerability analysis of a wide range of highway asset classes (pavement, bridge, culvert, ITS, etc.)
- Identify and develop multi-hazard approaches to risk assessment to account for the multiplicative effects of cascading and interactive threats.
- Develop a methodology for agency selection of top priority threats and assets combinations to conduct R&R assessments.
- Create working groups based on Subject Matter Experts (SMEs) from different state DOTs related to the different threats and asset selected for this study. SMEs will participate in multiple workshops to help develop and validate the different methodologies.
- Develop/establish methodologies for a quantitative assessment of:
  - Threat Frequency/Probabilities
  - Asset Vulnerability/Probabilities
  - Asset Valuation
  - Quantitative Consequences estimation
- Examine the incorporation of climate change projections into the risk assessments where applicable.

5. URGENCY AND POTENTIAL BENEFITS

While there are existing projects that address the subject of integrating R&R concepts into agency practice, so far, there are no projects that discuss quantitative risk assessment methodologies in-depth with standardized methodologies. Considering emerging threats, DOTs repeatedly have expressed an urgent need for new methods, metrics, tools, and resources for conducting quantitative risk assessments of the transportation system.

This project will help fill this gap with guidance on standardized methodologies for risk assessment.

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6. IMPLEMENTATION CONSIDERATIONS
In order to implement new risk assessment methodologies, senior executives and policy makers need to take the lead and champion these initiatives. Similarly, program managers need to take the major role in encouraging the implementation of new strategies at the program level. **What existing venues or processes could be used to support implementation?** Existing processes can be found in Transportation Agency Management Plans which typically include a section devoted to risk management and the agency's risk register. Many DOTs also follow FHWA's Vulnerability Assessment and Adaptation Framework. With respect to tools and technology, most DOTs have GIS to map and assess natural threats. In addition, the federal government offers a variety of tools, such as FHWA's Vulnerability Assessment Scoring Tool (VAST) and FEMA's HAZUS. Transportation agencies retain their own asset inventories, inspection records, and in some cases, custom-made hazard maps. However, federal and state agencies, for example, the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and Department of Homeland Security (DHS) provide public access to a broad selection of natural hazard layers.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD
The estimated total funds needed to accomplish the research objectives are roughly $1.5 M-$2 M. The level of effort of this project compared to the total level of effort for this phase of the roadmap (Phase 1) is approximately 40%. The timeframe to complete the research for this project is estimated to be 24-36 months of work. Based on the proposed roadmap for this program, this RPS is part of the three-year Phase 1 roadmap (to begin on year one of the program after the Highway R&R Manual is developed).

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS B2)
Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
Surveys of state DOTs reveal one of the barriers to conducting quantitative R&R assessments is the uncertainty surrounding the likelihood and physical and operational consequences from past adverse events. Further, transportation agencies generally do not have adequate databases or recording mechanisms for tracking such events. A frequently cited barrier to quantitative risk modeling is insufficient data for determining threat likelihoods, vulnerability, and consequences. Having a mechanism in place to capture data from events as they occur would help transportation agencies derive the threat frequencies, vulnerabilities, and consequences needed for quantitative risk models. This research will strive to develop a framework for recording and sharing historical data.

3. LITERATURE SEARCH SUMMARY

Below is a short list of some of the more relevant NCHRP projects that speak to quantitative methods of analysis for threats to asset condition and performance as well as those that worked to provide guidance on how to incorporate such analyses into decision making processes:

- NCHRP 08-87, Capitalizing on GIS and Asset Management
- NCHRP 20-45, Scientific Approaches to Transportation Research
- NCHRP 25-25(90), Application of Geographic Information Systems for Historic Properties
- NCHRP Synthesis 508: Data Management and Governance Practices

4. RESEARCH OBJECTIVE

The objective of this research is to develop a historical data capture process and system to support R&R modeling and assessments. Subtasks of this research include:

- Conduct of a state of practice review and gap assessment on how agencies collect and manage data from adverse events.
- Develop processes and tools for capturing past adverse events.
- Develop a data dictionary and database schema for R&R assessment.
- Develop an R&R management database that facilitates the searching and sharing of threat, asset, consequence, and other relevant attribute data.

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5. URGENCY AND POTENTIAL BENEFITS

DOTs have stressed the need for more data, tools, and metrics to assist in R&R assessments. DOTs are substantially more capable of conducting quantitative R&R assessments if they can aggregate their own maintenance and emergency repair data, as well as develop a collection plan to collect pre- and post-event data. A program for historical data capture will help DOTs derive the key variables needed for R&R assessment.

6. IMPLEMENTATION CONSIDERATIONS

To implement this data process, DOTs will have to consider the requirements (business areas, data required), assess existing data management capabilities and infrastructure, and define the technical aspects of the new or modified system for historical data capture. A flexible approach to adapting existing systems will greatly mitigate the level of effort as opposed to developing an entirely new data management system.

What existing venues or processes could be used to support implementation?

DOTs have asset management systems and data management systems (database, GIS) that can be leveraged to support a historical data capture program.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $200,000-$250,000. The level of effort of this project compared to the total level of effort for this phase of the roadmap (Phase 1) is approximately 10%.

The timeframe to complete the research for this project is estimated to be 12-18 months of work. Based on the proposed roadmap for this program, this RPS is part of the three-year Phase 1 roadmap. This project is expected to begin on year two or three of the roadmap.

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS B3)
Establishing a Quantitative Resilience Assessment Methodology for Transportation Highway Assets

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH

Traditionally, transportation planning has focused on addressing regularly occurring and observable disruptions while less attention has been given to less frequent, unpredictable events. However, in recent years more research has been devoted to resilience analysis of transportation networks to optimize emergency management and accelerate restoration schedules. AASHTO defines resiliency as, "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events." Risk management focuses on mitigating vulnerabilities and resilience management emphasizes rapid recovery and adaptation there is a high correlation. While transportation agencies regularly incorporate risk assessments in their transportation asset management plans, recent surveys indicate few agencies have conducted resilience assessments or developed resilience metrics. Findings from NCHRP Synthesis 20-05/48-13 published in 2018, "*Resilience in Transportation Planning, Engineering, Management, Policy, and Administration*" demonstrated there is a lack of understanding on how risk is related to resilience. In addition, it shows there is a need for more standardized resilience metrics and assessment methodologies that can help transportation agencies to understand the benefits of conducting these assessments and incorporating them into regular practice. Recognizing the Importance of resilience practices in the transportation sector, TRB published a report *"Investing in Transportation Resilience: A Framework for Informed Choices*". The report talks about the importance and challenges of maintaining a resilient transportation system and provides a review of practices by transportation agencies for evaluating resilience and conducting economic analysis to justify these investments.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of risk and resilience have been conducted through the NCHRP Process as well as TRB. Below is a short list of some of the more relevant NCHRP projects that speak to quantitative methods of analysis for threats to asset condition and performance as well as those that worked to provide guidance on how to incorporate such analyses into decision making processes:

- TRB Special Report 340 Consensus Study Reports to Congress. Investing in Transportation Resilience: A Framework for Informed Choices.
- NCHRP 20-125, Strategies for Incorporating Resilience into Transportation Networks
- NCHRP 15-80, Design Guide and Standards for Infrastructure Resilience
- NCHRP 08-36(146), Economic Resilience and Long-Term Highway/Transportation Infrastructure Investment
- NCHRP 08-129, Incorporating Resilience Concepts and Strategies in Transportation Planning
- NCHRP 20-59(54), Report 525 Vol 11: Disruption Impact Estimating Tool-Transportation (DIETT): A Tool for Prioritizing High-Value Transportation Choke Points
- NCHRP 20-59(14)C, Strategic Plan Implementation Support Services for SCOTSEM. Products: Understanding Transportation Resilience: A 2016-2018 Roadmap
- NCHRP 20-59(55), Transportation System Resilience: CEO Primer & Engagement

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- Products: NCHRP Research Report 976: Resilience Primer for Transportation Executives.
- NCHRP 20-59(56), Support for State DOT Transportation Systems Resilience and All-Hazards Programs
- NCHRP 20-117, Deploying Transportation Resilience Practices in State DOTs

4. RESEARCH OBJECTIVE

The objective of this research is to develop quantitative resilience assessment methodologies and metrics for transportation highway assets. This study will include:

- Assess the current state of practice on the process and incorporation of resilience assessments for highway assets through literature review, stakeholder interviews and a national survey. Sate of practice should include R&R models, metrics, tools, etc.
- Develop a resilience assessment purpose and need matrix that maps the existing use of resilience assessment efforts to the intended purpose and address success, challenges and needs.
- Develop a methodology to estimate resilience assessments building upon the developed risk assessment methodologies and framework from NCHRP 23-09 B1 and any new findings. Incorporate the relationship between R&R when developing the resilience methodology.
- Develop guidance explaining the relationship between R&R assessments.
- Identify data needs and sources.
- Develop guidance on methodologies for assessing network resilience and the appropriate metrics for commonly examined dimensions of resilience (e.g., safety, redundancy, adaptability, mobility, recovery, etc.)

5. URGENCY AND POTENTIAL BENEFITS

Recent scans have revealed that the terms “risk” and “resilience” are often used interchangeably or lumped together. In addition, there is no universal metric or set of metrics for resilience. However, DOTs have repeatedly expressed an urgent need for resilience metrics and assessment methodologies that extend beyond high level approaches.

6. IMPLEMENTATION CONSIDERATIONS

Competing priorities, insufficient resources, lack of perceived benefits, and lack of leadership are frequently cited barriers to the implementation of new R&R management initiatives. Leadership buy-in is crucial to successful implementation as well as interagency communication and collaboration.

What existing venues or processes could be used to support implementation?

Staff training, workshops, and agency guidance help coordinate the development of the resilience assessment program. GIS, data from maintenance and TIMS, and network modeling will support the pilot testing of resilience assessment metrics and methodologies.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $400,000-$500,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 1) is approximately 30%.

The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the three-year Phase 1 roadmap. This project is expected to begin on year one of the program.

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1. PROBLEM TITLE (RPS B4)
Establishing Considerations for Defining Risk and Resilience (R&R) Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
The National Highway Performance Program (23 U.S. Code § 119) compels transportation agencies to implement a risk-based asset management program. The first step towards managing an agency's risk is identifying the agency's risk appetite. Risk appetite is the cost that an agency is willing to absorb over a specific period of time to pursue objectives while risk thresholds are decision points that trigger a response when a certain level of risk has been reached. During multiple workshops for NCHRP projects, transportation professionals have frequently expressed a need for guidance on determining risk appetite and risk thresholds. It is important for a transportation agency to understand its appetite for risk to manage the balance between spending and being overly cautious to investment. Risk thresholds are the quantitative measures needed to keep an agency within its risk appetite. In addition, there is a need for more standardized methodologies to help state DOTs identify the most appropriate risk mitigation or resilience improvements strategies.

3. LITERATURE SEARCH SUMMARY
Several studies on the topic of R&R have been conducted through the NCHRP Process as well as TRB. Below is a short list of some of the more relevant NCHRP projects relevant to risk management. • NCHRP Synthesis 494, Life-Cycle Cost Analysis for Management of Highway Assets • NCHRP 20-101, Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change • NCHRP Synthesis 494, Life-Cycle Cost Analysis for Management of Highway Assets

4. RESEARCH OBJECTIVE
The intended outcome of this research project is to improve a DOT's decision making when selecting mitigation by providing guidance on metrics and methodologies for assessing a DOT's risk tolerance. Supporting tasks for this research project include: • Develop a process to aid organizations in the development of risk targets, risk tolerance, and risk thresholds (boundaries of acceptable risk) for strategic, programmatic, and daily operational risks. • Develop a decision-making process for determining what actions are taken when thresholds of acceptable risk are exceeded. • Develop the business case for supporting the use of risk thresholds, i.e., communicate the benefit of establishing risk thresholds to decision-makers. • Develop guidance on strategic investment decision making to include when to cease investing in assets that are either under-used or the cost of maintaining is no longer cost effective. • Develop a synthesis of the current practice for economic analysis (e.g., CBA, multi-criteria analysis, triple-dividend, etc.

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- Provide practical guidance on selection of risk mitigation and resilience improvement strategies: mitigate, transfer, avoidance, acceptance.
- Provide practical guidance on selecting the best approach for project appraisal
- Parameter selection
- Analytical steps.
- Metrics (e.g., Net Present Value (NPV), Internal Rate or Return, cost effectiveness, etc.)

5. URGENCY AND POTENTIAL BENEFITS

In the face of climate change, federal mandates, and the challenge of prioritizing limited resources, DOTs have repeatedly expressed a need for more tools, methodologies, and metrics for R&R assessment. On November 16, 2021, President Biden signed the Infrastructure Investment and Jobs Act (IIA), recognizing that building resilience into the nation's infrastructure is critical to the nation. In light of the non-stationarity of climate change, DOTs are finding that a rigid approach to design is no longer realistic. Instead, DOTs need to take a risk management approach and reassess the resilience of their systems, periodically, over time. The first step in developing this risk management approach is establishing risk targets or tolerances for their assets.

6. IMPLEMENTATION CONSIDERATIONS

Implementation starts with leadership evaluating the organization's maturity in terms of knowledge, capabilities, tools, methodologies, and data, followed by a plan to address any implementation gaps. Leadership buy-in will be necessary to overcome any institutional barriers to implementation such as staff attitudes, lack of training, lack of resources, and technical problems.

What existing venues or processes could be used to support implementation?

Transportation agencies can begin with existing agency risk assessment methodologies (e.g., risk registers) and performance metrics from the agency's Transportation Asset Management Plan.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $250,000-$300,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 1) is approximately 20%.

The timeframe to complete the research for this project is estimated to be 12-18 months of work. Based on the proposed roadmap for this program, this RPS is part of the three-year Phase 1 roadmap. This project is expected to begin on year two or three of the program.

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Phase 2 - Pilot testing and implementation of "Highway Risk & Resilience (R&R) Manual"

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS A1)

Developing Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH

Effective implementation of R&R approaches and management are integrated throughout a transportation agency and particularly involves senior leadership, data and tools resources and performance and asset management efforts. Performance and asset management processes are typically more mature in their development and can benefit by improving and collaborating R&R efforts. However, the development and integration of R&R are less mature in most agencies. Collaboration and communication among different areas and groups within an agency (e.g., asset management, design, operations, maintenance, IT, etc.) helps with information and data sharing and are key for R&R implementation. Similarly, collaboration with external agencies such as Metropolitan Planning Organizations (MPOs), cities, environmental and science groups among many other agencies will also facilitate data and information sharing for conducting R&R assessments.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of risk and resilience have been conducted through the NCHRP Process as well as FHWA and a few state DOTs. Below is a short list of some of the more relevant NCHRP projects that address collaboration and communications strategies within the transportation sector:

- NCHRP 20-117, Deploying Transportation Resilience Practices in State DOTS
- NCHRP 08-113, Integrating Effective Transportation Performance, Risk, and Asset Management Practices
- NCHRP 20-127, Business Case and Communications Strategies for State DOT Resilience Efforts
- NCHRP 08-128, Snapshots of Planning Practice
- NCHRP 20-24(74), Executive Strategies for Risk Management by State Departments of Transportation
- NCHRP 20-59(55), Transportation System Resilience: CEO Primer & Engagement
- NCHRP 08-36(142), Guidebook for Multi-Agency Collaboration for Sustainability and Resilience
- NCHRP 08-129, Incorporating Resilience into Transportation Planning

The proposed program of projects would work to integrate this research and extend methods for collaboration and communicating risk and resilience into a single manual to ease the burden of the profession when seeking information from disparate sources.

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4. RESEARCH OBJECTIVE

The objective of this research is to develop effective internal and external communication and collaboration practices transportation agencies have implemented and develop guidance on promoting and enhancing these practices.

The specific research tasks to accomplish the main objective include:

- Conduct a state of practice review of communication and collaboration practices, policies, strategies and tools through literature review and stakeholder engagement.
- Conduct a gap assessment of existing practices and how they are responding to the objectives behind R&R efforts at transportation agencies.
- Conduct case studies of successful communication and collaboration practices applied in existing situations and follow-up with relevant transportation agencies with stakeholder interviews to define the reasons and means by which the practices were successful.
- Perform a qualitative assessment on identified and classified practices.
- Develop strategies for communication and collaboration within multi-disciplinary agency groups as well as with other agencies in order to implement Highway R&R Manual and management framework.
- Develop strategies to facilitate media outreach.
- Develop strategies for communicating uncertainty in risk and resilience models and assessments.
- Develop strategies for facilitating internal collaboration across functional areas and divisions.
- Develop strategies for facilitating external collaboration with stakeholders and partners.

5. URGENCY AND POTENTIAL BENEFITS

From the literature review, there does not seem to be any previous or ongoing research focusing on this topic. Communities across the nation are facing multiple shocks from extreme weather, disasters, and climate change. Improved communication and collaboration between transportation agencies and stakeholders shortens response times and speeds up recovery from adverse events. In contrast, the absence of a plan for communications and collaboration risks prolonging recovery and increasing the pain suffered by the local community.

This project will help state DOTs more effectively organize to collaborate on complex problems as well as communicate risk and resilience management objectives and the use of the Risk and Resilience Highway manual with stakeholders and partners.

6. IMPLEMENTATION CONSIDERATIONS

In order to implement new collaboration and communications strategies, senior executives and policy makers need to take the lead and champion these initiatives. Similarly, program managers need to take the major role in encouraging the implementation of new strategies at the program level.

What existing venues or processes could be used to support implementation?

It is key that senior executives, policy makers and program managers need to have a communication plan to communicate with peers in order to effectively integrate risk management. Additional products and activities, like training workshops to increase the integration of risk management into maintenances practices, as well as peer exchanges and informative presentations can help state DOTs positively impact their organization.

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7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD
The estimated total funds needed to accomplish the research objectives are roughly $250,000-$300,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 2) is approximately 20%. The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 2 roadmap. This project is expected to begin on year four of the program after the Highway R&R Manual is developed.

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS A2)
Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency (R&R) Assessments at Transportation Agencies

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
Recent state-of-the-practice reviews have revealed that transportation agency staff are not adequately trained or in possession of the necessary data or institutional support to effectively conduct R&R assessments. Extreme weather, climate change, pandemics, and cybersecurity breaches have spotlighted the need for greater investment in R&R research. Part of this research should focus on assisting transportation agencies to cultivate the resources they need to effectively conduct R&R assessments.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of risk and resilience have been conducted through the NCHRP Process as well as FHWA. Below is a brief list of some of the more relevant NCHRP projects:

- NCHRP 20-105B, Development of Course Outlines for Ahead of the Curve Training Program: Mastering the Management of Transportation Research
- NCHRP 20-117, Deploying Transportation Resilience Practices in State DOTs
- NCRHP 362, Synthesis Training Programs, Processes, Policies, and Practices
- NCHRP 20-24(95), Transportation Agency Capability Building Web-Based Guide Quick Reference
- NCHRP 20-105B, Development of Course Outlines for Ahead of the Curve Training Program: Mastering the Management of Transportation Research
- NCRHP 362, Synthesis Training Programs, Processes, Policies, and Practices
- NCHRP 20-125, Strategies for Incorporating Resilience into the Transportation Network

4. RESEARCH OBJECTIVE

The objective of this research is to develop a capacity building plan to identify and develop adequate training, guidance, and the leadership support (funding, inter-agency collaboration, data procurement) that transportation agencies need to make implementation and training on the Highway R&R Manual feasible and effective.   The specific research tasks to accomplish the main objective include:

- Explore best practices in institutional training programs and data collaboration policies both within R&R as well as more mature management practices such as asset management.
- Use agency interviews and peer exchange to investigate individual and institutional gaps and needs in staff skills and program policies and structure.

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- Assess available training programs in academic or professional development forums and their alignment in providing the skills necessary for a more mature development and assessment of risk and resilience.
- Provide guidance with recommendations on R&R skills and development programs available, being developed and needing to be developed to provide effective individual support in necessary skills training.
- Develop training material for agencies to implement Highway R&R Manual.
- Develop a train-the-trainer program.

5. URGENCY AND POTENTIAL BENEFITS

While there are several past and active NCHRP projects that relate to R&R assessment, so far, there do not appear to be any projects that have focused on the topic of capacity building for R&R assessment. In the face of increasing threats, aging infrastructure, and limited resources, there is a pressing need from agencies for processes and tools to build their capacity for conducting more robust R&R assessments. Without adequate capacity, transportation agencies will struggle in their planning efforts to effectively address challenges to their system's resilience.

6. IMPLEMENTATION CONSIDERATIONS

Developing a capacity and resource plan is the responsibility of executives, key leadership, and program managers. DOTs need to communicate across functional areas to determine the existing capacity and resource needs of their respective departments and consider all types of organizational capacity, including leadership, management, and technical. All capacity building activities benefit from having champions who have capacity building as a top priority.

What existing venues or processes could be used to support implementation?

Recommended sources and support for capacity building include training and workshops, peer exchanges, consultancies, university research centers, and professional organizations like AASHTO. In addition, DOTs should leverage in-house expertise and existing knowledge management and data management systems to share information and tools, host online training, etc.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $250,000-$300,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 2) is approximately 20%.

The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 2 roadmap. This project is expected to begin on year four of the program after the Highway R&R Manual is developed.

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS A3)
Pilot Testing the Risk and Resilience (R&R) Highway Manual and Interface with Existing Asset Management Systems and Other Agency Functions

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
Projects NCHRP 23-09 RPS B1, RPS B3, RPS B4 will result in the development of methodologies for conducting R&R analysis for highway assets to be integrated with existing systems for a more efficient use.

3. LITERATURE SEARCH SUMMARY
Several studies on the topic of R&R have been conducted through the NCHRP Process as well as FHWA and used on the development of the R&R Highway Manual. In addition, similar NCHRP studies have also pilot tested the development of guidance under the NCHRP 20-44 Implementation and Support Program. Two similar pilot studies include NCHRP 20-44(23) which pilot tests the *Climate change Design Practices Guide for Hydrology and Hydraulics* developed under NCHRP 15-61, and NCHRP 20-44(41) that pilot tests *the Deployment of Transportation Resilience Practices in State DOTs* developed under NCHRP 20-117.

4. RESEARCH OBJECTIVE

The objective of this implementation project is to conduct pilot tests in concert with several state Departments of Transportation (DOTs) to determine the effectiveness and ease of implementation of the risk and resilience assessment methodologies for highway assets developed for the Highway R&R Manual. The project will:

- Select state DOTs to participate in the pilots. Selecting of state DOTs will be based on the range of threats and highway assets included in that R&R Highway Manual as well as maturity of agency on conducting R&R assessments.
- Assist and guide state DOT to conduct the pilot projects and the application of the different developed methodologies as applicable.
- Conduct a survey to assess the level of effort and understanding of the methodologies when conducting the pilots.
- Conduct multiple workshops with state DOT participating in the pilots.
- Conduct a robust evaluation of the methodologies against a consistent set of metrics, illuminating the refinements needed to improve the product.
- Propose revisions and refinements of the methodologies on the Highway R&R Manual.

The proposed program of projects would serve to support managing the testing and validation of the highway risk and resilience manual by DOTs.

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5. URGENCY AND POTENTIAL BENEFITS
From the literature review, there does not seem to be any previous or ongoing research that tests the implementation of a standard for highway risk and resilience assessment. Recent scans of DOTs have revealed an urgent need for new R&R assessment methodologies, tools, and technologies. Numerous active projects will advance the transportation sector's understanding of the R&R process; however, this will require validation of the new approaches. This project will provide opportunities to transportation agencies to exercise the methodologies from the highway manual and feedback that will prove invaluable for refining the manual.

6. IMPLEMENTATION CONSIDERATIONS
Testing the new highway manual for R&R will require leadership buy-in and R&R champions within the agency to make the business case for implementing new methodologies and to organize the necessary collaboration and communication required to manage the complexities of the task. **What existing venues or processes could be used to support implementation?** DOTs can leverage experiences from their existing practices found in their risk-based asset management plans, as well as experience from participation in FHWA-sponsored risk and resilience studies or other similar efforts.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD
The estimated total funds needed to accomplish the research objectives are roughly $450,000-$500,000. The level of effort of this project compared to the total level of effort for this phase of the roadmap (Phase 2) is approximately 40%. The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 2 roadmap. This project is expected to begin on year four of the program after the Highway R&R Manual is developed.

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS A4)
Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of Highway R&R Manual.

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
Mainstreaming and integrating R&R assessments into DOT practices will require changes to DOT's IOP arrangements from existing traditional programmatic approaches to incorporate risk-informed decision-making and enhanced resilience as the frequency, intensity, and scope of disruptions increased. Effective integration of R&R assessment results into decision-making will require the identification of risk-informed and resilience-sensitive actions to make DOT functions more responsive and agile to emerging needs and conditions.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of risk and resilience have been conducted through the NCHRP Process, TRB, and FHWA research. Below is a short list of some of the more relevant NCHRP projects:

- NCHRP 08-36(144) Transportation Asset Management and Effective Organizational Models for Program Implementation
- NCHRP 08-113 Integrating Effective Transportation Performance, Risk, and Asset Management Practices
- NCHRP 20-59(54) Transportation System Resilience: Research Roadmap and White Papers
- NCHRP 20-59(55) Transportation System Resilience: CEO Primer & Engagement
- NCHRP 20-117 Deploying Transportation Resilience Practices in State DOTs.
- FHWA Integrating Natural-Hazard Resilience into Transportation Planning-White Paper on Literature Review Findings
- TRB Special Report 340 Investing in Transportation Resilience: A Framework for Informed Choices

4. RESEARCH OBJECTIVE

The object of is this research is to recommend IOP changes and provide transportation agencies with strategies and tools for successful adoption of the Highway R&R Manual.

The specific research tasks to accomplish the main objective include:

- Conduct a review of best practices for implementation and development strategies.
- Develop an action plan for a systematic integration of the results of R&R assessments to transition to integrate risk management and resilience-sensitive decision-making. IOP changes will target realignment of agency processes, identify responsibility at various levels of decision-making, and highlight areas where organizational changes need to be made to augment the effectiveness of an R&R-informed DOT management practices.
- Develop decision tools that align with federal funding mechanisms.
- Make a business case for integrating R&R results into DOT practices and decision-support systems by demonstrating the needs and benefits of the proposed IOP changes.

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- Illustrate how agencies can assess and transition from their current legacy IOP arrangements to an R&R-informed framework.

5. URGENCY AND POTENTIAL BENEFITS

From the literature review, there does not seem to be any previous or ongoing research focusing on the topic of organizational readiness for the implementation of new strategies in particular for risk and resilience assessments. The willingness and capacity of all relevant stakeholders to consider new practices and support for change management needs is critical for promoting the adoption of new risk and resilience assessment methods and improving implementation outcomes. However, no research in the transportation sector currently guides the enhancement of organizational readiness for implementation.

This project will help state DOTs improve their readiness for implementation of the new R&R assessment strategies developed on the Highway R&R Manual across the agency.

6. IMPLEMENTATION CONSIDERATIONS

Organizational climate and individual attitudes can pose as barriers to the successful implementation of new initiatives. In order to implement new IOP strategies, senior executives and policy makers need to take the lead and champion these initiatives. Similarly, program managers need to take the major role in encouraging the implementation of new strategies at the program level.

What existing venues or processes could be used to support implementation?

Agency Standard Operating Procedures (SOP) and policies, organizational structure, and collaborative activities, such as workshops and Delphi sessions could support successful implementation.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $250,000-$300,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 2) is approximately 20%.

The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 2 roadmap. This project is expected to begin on year four of the program after the Highway R&R Manual is developed.

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Phase 3 - Development of tools and revision of "Highway Risk & Resilience (R&R) Manual"

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS A5)
Enhancing the Capacity Building and Implementation Plans to Incorporate the Highway Risk and Resilience (R&R) Manual Tools

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
This project is an enhancement of RPS(s) A2 - *Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct R&R Assessments at Transportation Agencies* and A4 ***- Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of Highway R&R Manual*** to include findings from RPS(s) C1 and C2 – *Developments of tools for Risk and Resilience Assessments*. DOTs have expressed an urgent need for more tools for R&R assessment. This project will ensure state DOTs will receive the necessary training on the new tools and methodologies to ensure successful implementation and integration with agency practices and tools

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of risk and resilience have been conducted through the NCHRP Process. Below is a short list of some of the more relevant NCHRP projects:

- NCHRP 08-118, Risk Assessment Techniques for Transportation Asset Management
- NCHRP 20-105B, Development of Course Outlines for Ahead of the Curve Training Program: Mastering the Management of Transportation Research
- NCHRP 20-117, Deploying Transportation Resilience Practices in State DOTs
- NCHRP 20-123(04), Development of a Risk Management Strategic Plan and a Research Roadmap
- NCRHP 362, Synthesis Training Programs, Processes, Policies, and Practices
- NCHRP 658, Guidebook on Risk Analysis Tools and Management Practices to Control Transportation Project Costs
- NCHRP 20-24(95), Transportation Agency Capability Building Web-Based Guide Quick Reference

4. RESEARCH OBJECTIVE

The objective of this research is to assist transportation agencies in developing plans for capacity building and implementation of the Highway R&R Manual and associated tools. The specific research tasks to accomplish the main objective include:

- Develop learning objectives and course outline.
- Develop training materials in accordance with principles of Instructional System Development (ISD).
- Present draft materials to a joint working session of the NCHRP Panel.
- Conduct multi-state DOT pilot study implementations of the training plan and materials.
- Conduct an evaluation of the pilot studies.
- Develop a follow-on train-the-trainer course.

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5. URGENCY AND POTENTIAL BENEFITS
The focus of the Highway R&R Manual is demonstrating methodologies and tools for conducting quantitative R&R assessments. Guidance is needed to ensure the successful implementation of this manual. This will require guidance on how to integrate the manual into agency practices as well as training for engineers and planners on employing the methodologies and tools described in the manual. The Highway R&R Manual will take a major step towards advancing the state of the practice of R&R assessment within the surface transportation sector.

6. IMPLEMENTATION CONSIDERATIONS
Factors that impact implementation include: • Existing policies and procedures • Technology • Data and data management • Agency leadership and culture • Previous experience with risk and resilience assessment methodologies and tools Factors that accelerate the use and implementation of quantitative R&R assessment methodologies include R&R champions with the agency and new policies promoting R&R assessment. **What existing venues or processes could be used to support implementation?** DOTs have a variety of tools for implementing training, including webinars, online training videos, workshops, peer exchanges, professional development programs, and knowledge management programs.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD
The estimated total funds needed to accomplish the research objectives are roughly $150,000-$200,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 3) is approximately 10%. The timeframe to complete the research for this project is estimated to be 12-18 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 3 roadmap. This project is expected to begin in year six or seven of the program after the Highway R&R Manual and tools are developed and pilot tested.

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS A6)
Revising the Highway Risk and Resilience (R&R) Manual

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH
This project builds upon the work conducted for RPS(s) B1, B3, B4 to develop the Highway R&R Manual methodologies and RPS A3, Pilot Test Risk and Resilience Highway Manual and Interface with Existing Asset Management Systems and Other Agency Functions. Pilot tests were conducted in concert with several departments of transportation (DOTs) to determine the effectiveness and ease of implementation of the Highway R&R Manual. The objective of this project is to synthesize lessons learned from the pilot tests for refining the Highway R&R Manual as well as recommend protocols for periodic revisions of the manual: for example, updates in climate and other environmental data and data sources, changes in regulatory requirements, new versions of cited tools, newly released tools, etc.

3. LITERATURE SEARCH SUMMARY
Several studies on the topic of risk and resilience have been conducted through the NCHRP Process as well as FHWA. In addition, similar NCHRP studies have also pilot tested the development of guidance under the NCHRP 20-44 Implementation and Support Program with follow-up projects to provide revisions to the original guidance document based on pilot feedback. A similar pilot studies include NCHRP 20-44(23) which pilot tests the *Climate change Design Practices Guide for Hydrology and Hydraulics* developed under NCHRP 15-61 and will provide recommendations for guidance improvement and enhancement on NCHRP 15-61A - *Updates to the Design Practices Guide for Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure.*

4. RESEARCH OBJECTIVE
The research objective is to synthesize the recommendations from state DOTs that have tested implementation of the draft Highway R&R Manuals. The proposed implementation efforts and associated services will include the following: • Kickoff and orientation meeting for each participating agency. • Virtual or On-Site Workshops with state DOTs to discuss gaps in the Manual and propose solutions. • Peer Exchange among DOTs to share lessons learned from the pilot tests. • Recommendations for procedures and protocols for periodic update of the Manual. • Synthesis of results to be compiled in a final report with recommendations for improving the Manual.

5. URGENCY AND POTENTIAL BENEFITS
This project is necessary to validate and improve upon past NCHRP research and investment into development of the Highway R&R Manual. Refining the manual based on input from state DOTs will result in guidance that state DOTs can more effectively integrate with their existing practices.

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6. IMPLEMENTATION CONSIDERATIONS
Successful implementation will require leadership and internal collaboration to get staff on board with making changes to existing practices and updating appropriate policies, documents, and procedures to reflect the new changes. **What existing venues or processes could be used to support implementation?** Existing agency approaches to R&R assessments can be found in Transportation Asset Management Plans that include a section devoted to risk management. In addition, many agencies have special programs that focus on specific aspects of risk and resilience: geotechnical hazard management, scour management, safety, and emergency management programs. In-house data (asset inventory, hazard data, maintenance records) and GIS staff can be leveraged to implement new models.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD
The estimated total funds needed to accomplish the research objectives are roughly $200,000-$250,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 3) is approximately 10%. The timeframe to complete the research for this project is estimated to be 12-18 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 3 roadmap. This project is expected to begin on year six or seven of the program after the Highway R&R Manual and tools are developed and pilot tested.

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FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS C1)

Identifying and Developing Analytical Tools to Conduct Risk Assessments for Highway Assets

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH

Currently there are no standardized methods and tools to undertake risk assessments. This makes it difficult to assess risk to transportation infrastructure in a manner that can be communicated using standard sets of commonly adopted metrics. Tools that are proposed to be developed as part of this research will assess, report, and communicate the results of the assessment – consistent with the Highway R&R Manual methodologies developed in RPS B1.

This research will build on the NCHRP 23-09 literature review on tools and technologies that are available in the state of practice to conduct R&R assessments. It will also build on the gap analysis that has been conducted to address the shortfalls of existing tools in developing/choosing a quantitative methodology for implementation that is consistent, and easy to communicate to a range of audiences including decision-makers and public as the basis for investing in resilience improvements/investments.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of R&R have been conducted through the NCHRP Process. Below is a short list of some of the more relevant NCHRP projects that speak to risk assessment for transportation.

- NCHRP 23-24, Develop Methods to Allow Agencies to Incorporate Quantitative Risk Assessment at Project and Network Level
- NCHRP 08-118, Risk Assessment Techniques for Transportation Asset Management
- NCHRP 20-125, Strategies for Incorporating Resilience into Transportation Networks

4. RESEARCH OBJECTIVE

The objective of this research is to identify and develop a set of practical and easy to use tools that will help implement risk assessment methodologies developed for the Highway R&R Manual. These tools will enable implementation of risk methodologies developed during NCHRP 23-09 RPS B1 - *Establishing a Quantitative Risk Assessment Methodology for Highway Assets/Networks for Top Priority Hazards/Threats (Phase 1)* including scoping, assessment, evaluation, and the integration of the results into DOT's business processes.
Potential Tasks:

- Conduct a review of readily available tools currently used by state DOTs.
- Select methods that are general enough to accommodate existing frameworks including FHWA's Vulnerability Assessment and Adaptation Framework (VAAF), RAMCAP, etc.
- Develop tools that are GIS-based, quantitative, facilitate analysis at a point in time and as a function of time, easy to use, and require minimal training.
- Develop tools to capture historical and maintenance data for improving threat, vulnerability, and consequence models.

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- Develop tools for estimating asset/system criticality.
- Develop tools for estimating threat likelihood.
- Develop quantitative tools for assessing vulnerability to highway assets.
- Develop quantitative tools for estimating direct and indirect consequences of adverse events.
- Develop tools to calculate return on investment and conduct standard benefit-cost analysis.
- Develop metrics and communication strategies for reporting the results of risk assessments for the purposes of planning, prioritization, screening, scoping, evaluation, etc.
- Develop strategies for integrating the outputs of with asset management models and systems data availability and suitability for assessments.

5. URGENCY AND POTENTIAL BENEFITS

Recent scans of transportation agencies reveal the most common risk assessment tool is still the risk register. Risk registers are qualitative and thus do not support the decision making necessary for prioritizing projects, investing, or changing project designs. During recent NCHRP workshops, Transportation Agencies have repeatedly expressed a need for tools for R&R assessment. The need is urgent because of growing pressure from the public and government to take into consideration emerging threats such as climate change and extreme weather. The potential benefits include significant cost savings over the life cycle of a facility due to effective risk management founded on robust, quantitative R&R assessments.

6. IMPLEMENTATION CONSIDERATIONS

Implementation considerations include the staffing and training requirements to support R&R assessments as well as technical issues related to integrating new tools into existing frameworks.

What existing venues or processes could be used to support implementation?

Staff with interest and experience in R&R assessment, partnerships with consultancies and university research centers, peer exchanges with other DOTs, workshops, and agency-developed tools can support implementation.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $800,000 -$1,000,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 3) is approximately 50%.

The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 3 roadmap. This project is expected to begin on year six of the program after the Highway R&R Manual is pilot tested.

8. PROBLEM STATEMENT AUTHOR(s): *For each author, provide their name, affiliation, email address and phone.*

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9. POTENTIAL PANEL MEMBERS: *For each panel member, provide their name, affiliation, email address and phone.*

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To be selected in the future by the National Cooperative Highway Research Program (NCHRP)

10. PERSON SUBMITTING THE PROBLEM STATEMENT: *Name, affiliation, email address and phone.*

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American Association of State Highway and Transportation Officials
Special Committee on Research and Innovation

FY(TBD) NCHRP PROBLEM STATEMENT

1. PROBLEM TITLE (RPS C2)

Identifying and Developing Analytical Tools to Conduct Resilience Assessments for Highway Assets

2. BACKGROUND INFORMATION AND NEED FOR RESEARCH

Currently there are no standardized tools and methods to undertake resilience assessments. This makes it difficult to assess the resilience of transportation infrastructure in a manner that can be communicated using standard sets of commonly adopted metrics. Tools that are proposed to be developed as part of this research will assess, report, and communicate the results of the assessment – consistent with the resilience assessment methodologies developed in RPS B3.

This research will build on the NCHRP 23-09 literature review on tools and technologies that are available in the state of practice to conduct resilience assessments. It will also build on the gap analysis that has been conducted to address the shortfalls of existing tools in developing/choosing a quantitative methodology for implementation that is consistent, and easy to communicate to a range of audience including decision-makers and public as the basis for investing in resilience improvements/investments.

3. LITERATURE SEARCH SUMMARY

Several studies on the topic of resilience have been conducted through the NCHRP Process. Below is a short list of some of the more relevant NCHRP projects that speak to quantitative methods of analysis for threats to asset condition and performance as well as those that worked to provide guidance on how to incorporate such analyses into decision making processes:

- NCHRP 08-36(146), Incorporating Resilience into Transportation planning and Assessment
- NCHRP 20-59(54), Resilience Research Roadmap
- NCHRP 20-117, Deploying Transportation Resilience Practices in State DOTs
- NCHRP 20-125, Strategies for Incorporating Resilience into Transportation Networks
- NCHRP 08-129, Incorporation of Resilience Effort into Transportation Planning

4. RESEARCH OBJECTIVE

The objective of this research is to identify and develop a set of practical and easy to use tools that will help implement resilience assessment methodologies at State DOTs. These tools will enable implementation of resilience methodologies developed during NCHRP 23-09 RPS B3 - *Develop a Quantitative Resilience Assessment Methodology for Transportation Highway Assets/Networks* including scoping, assessment, evaluation, and the integration of the results into DOT's business processes. These tools should build upon and relate to the risk assessment tools developed from RPS C1 for consistency of application.

Potential Tasks:

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- Conduct a scan of the current state of practice by DOTS to include resilience metrics and resilience assessment tools.
- Develop metrics and communication strategies for reporting the results of resilience assessments for the purposes of planning, prioritization, screening, scoping, evaluation, etc.
- Develop quantitative resilience assessment tools that facilitate analysis at a point of time and as a function of time, easy to use, and require minimal training.
- Develop strategies for integrating the outputs of with asset management models and systems data availability and suitability for assessments.

5. URGENCY AND POTENTIAL BENEFITS

Recent scans of transportation agencies reveal that the most common risk assessment tool is still the risk register. Risk registers are qualitative and thus do not support the decision-making necessary for prioritizing projects, investing, or changing project designs. During recent NCHRP workshops, transportation agencies have repeatedly expressed a need for tools for R&R assessment. The need is urgent because of growing pressure from the public and government to take into consideration emerging threats such as climate change and extreme weather. The potential benefits include significant cost savings over the life cycle of a facility due to effective resilience management founded on robust, quantitative R&R assessments.

6. IMPLEMENTATION CONSIDERATIONS

Implementation considerations include the staffing and training requirements to support R&R assessments as well as technical issues related to integrating new tools into existing frameworks.

What existing venues or processes could be used to support implementation?

Staff with interest and experience in R&R assessment, partnerships with consultancies and university research centers, peer exchanges with other DOTs, workshops, and agency-developed tools can support implementation.

7. RECOMMENDED RESEARCH FUNDING AND RESEARCH PERIOD

The estimated total funds needed to accomplish the research objectives are roughly $500,000-$600,000. The level of effort of this project compared to the total level of effort for this phase of the Roadmap (Phase 3) is approximately 30%.

The timeframe to complete the research for this project is estimated to be 18-24 months of work. Based on the proposed roadmap for this program, this RPS is part of the two-year Phase 3 roadmap. This project is expected to begin on year six of the program after the Highway R&R Manual is pilot tested.

8. PROBLEM STATEMENT AUTHOR(s): *For each author, provide their name, affiliation, email address and phone.*

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APPENDIX E – TECHNICAL MEMORANDUM – STATEHOLDER ENGAGEMENT

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TASK 3: STAKEHOLDER ENGAGEMENT

NCHRP PROJECT 23-09

SCOPING STUDY TO DEVELOP THE BASIS FOR A HIGHWAY STANDARD TO CONDUCT AN ALL-HAZARDS RISK AND RESILIENCE ANALYSIS

TASK 3 DELIVERABLE – TECHNICAL MEMORANDUM

Prepared by

AEM Corporation

Jacobs Engineering Group

Cambridge Systematics

September 30, 2021

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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Table of Contents

Introduction

This memorandum documents the third of three interactive, online stakeholder engagements. The first two were conducted in March and April of 2021. These workshops served to validate the gaps identified during the literature review and to get a pulse on where the agencies feel they are currently in terms of risk and resilience tools, metrics, and methodologies. The third workshop, conducted on September 22nd, 2021, served to validate the proposed research problem statements and research roadmap.

Objective

The third workshop had two objectives:

1. Validate the research topics and problem statements (RPS).
2. Validate the research roadmap.

The research team presented two different roadmap options and a total of 12 research problem statements. The goal of the research team was to engage stakeholders in a discussion, supplemented with an interactive online platform, to obtain feedback concerning the selection and prioritization of RPS as well as stakeholder preference for the two proposed research options.

Research Task Approach - Procedure and Participation

Twenty states plus the District of Columbia were represented (see Figure 1) with 35 participants from State DOTs, US DOT, FHWA, local agencies, academia, and the private sector. Prior to the workshop, all invitees were sent a read-ahead packet which included detailed descriptions of the following:

1. Framework for Conducting Quantitative Risk and Resilience Assessments to Physical Highway Infrastructure
2. Research Roadmap to Develop and Adopt a Highway Standard/Guidance for R&R Assessments, including graphic illustrations of two research roadmap options
3. Complete catalog of 12 proposed research problem statements

The Industry Workshop for Roadmap Validation was conducted in two parts – a PowerPoint presentation, followed by an interactive session with Mural, a virtual whiteboard that facilitates visual collaboration.

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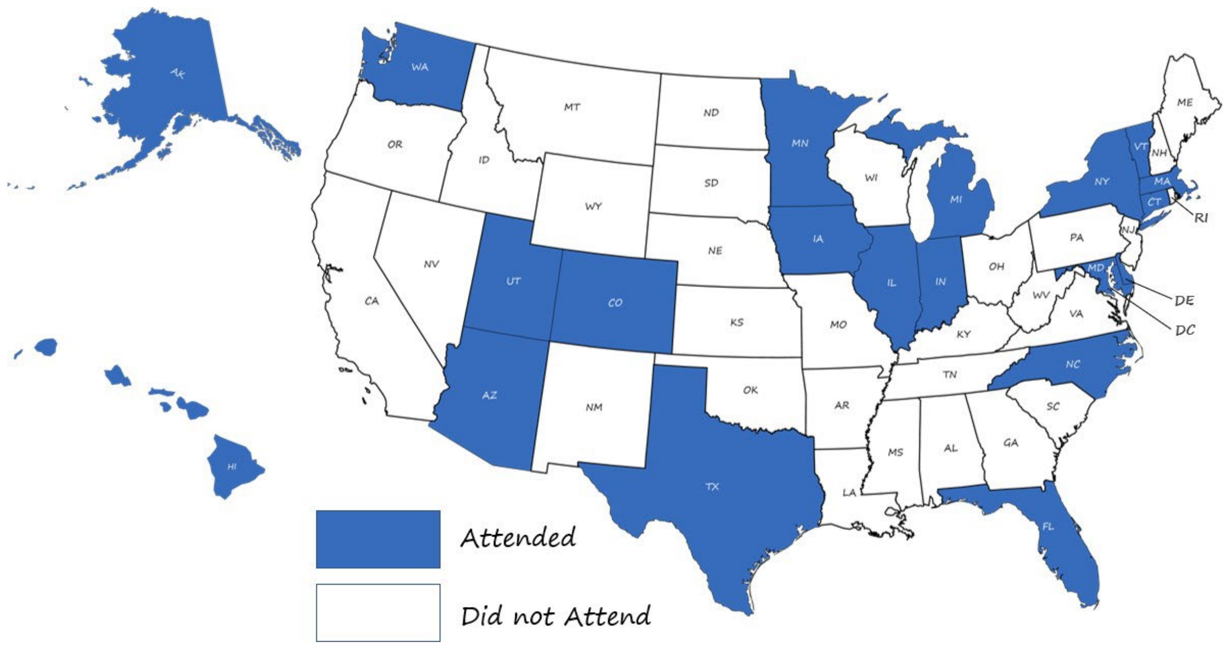

Figure 1. Map of Workshop Attendees

The presentation provided a project overview and summary of the tasks completed to date, followed by a discussion of the proposed risk and resilience framework and roadmap with corresponding RPS. At the end of the presentation, the participants were asked if they agreed with the mission, goals and objectives. Two participants emphasized the importance of Roadmap Development Goal, number 2: "Define a consistent framework for risk and resilience assessment that identifies core processes and methods." Another participant expressed how he liked the focus on highway assets in the Roadmap Development Mission: "Our mission is to create an efficient guidance for state DOTs to implement consistent physical transportation highway asset risk and resilience processes within and among organizations for improved sustainability." Others voiced concern about the order of the steps outlined in the framework, that perhaps asset characterization should be done before threat characterization (see Figure 2). The research team suggested that the exact order of the steps is not necessarily fixed, and the Framework was going to be revised.

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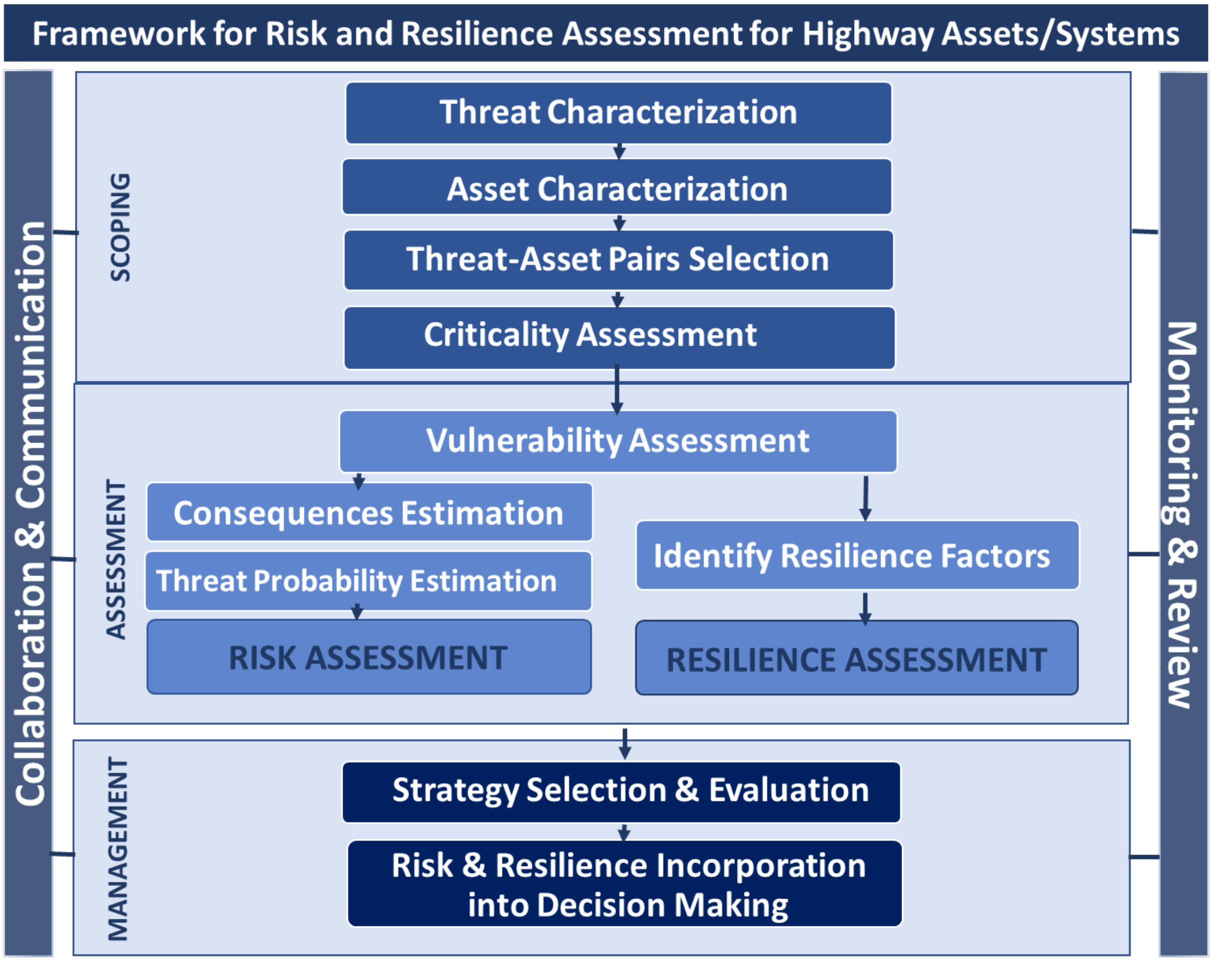

Figure 2. Risk and Resilience for Highways Framework

There was also some discussion about whether risk and resilience can be separated in an analysis. The research team explained that while risk and resilience overlap and are related, there are still differences that warrant separate methodologies and metrics – risk has a greater connection to vulnerability while resilience has a greater connection to recovery after an event. One of the participants summarized that before an agency can successfully perform a detailed, granular assessment, it must first have a well-thought-out high-level understanding of risk and resilience including an agency agreed upon definition of resilience and an overall risk and resilience narrative, i.e., an awareness of what are the critical threats facing the agency's assets.

After the slideshow presentation, the workshop attendees were instructed to join in an interactive session with Mural. The Mural session engaged the participants with 5 activities:

- **Activity 1:** Brainstorming of topics to be covered in the Roadmap by Thematic Lane.

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- **Activity 2:** Mapping Roadmap topics to existing RPS.
- **Activity 3:** Development of New RPS based on NEW topics from Activity 3.
- **Activity 4:** Discussion of Roadmap options.
- **Activity 5:** Selection of priority topics for Roadmap.

The Mural itself was organized into 8 boards to cover the 5 activities (see Table 1 and Figure 3):

Table 1. Mural Board and Corresponding Activities

Board	Name	Activity Number
1	How Does This Work?	N/A
2	Power On!	N/A
3	Topics We Need to Cover	1
4	Mapping Exercise	2
5	Break Time	N/A
6	Develop New Problem Statements	3
7	Choose Roadmap Options	4
8	Prioritize RPS	5

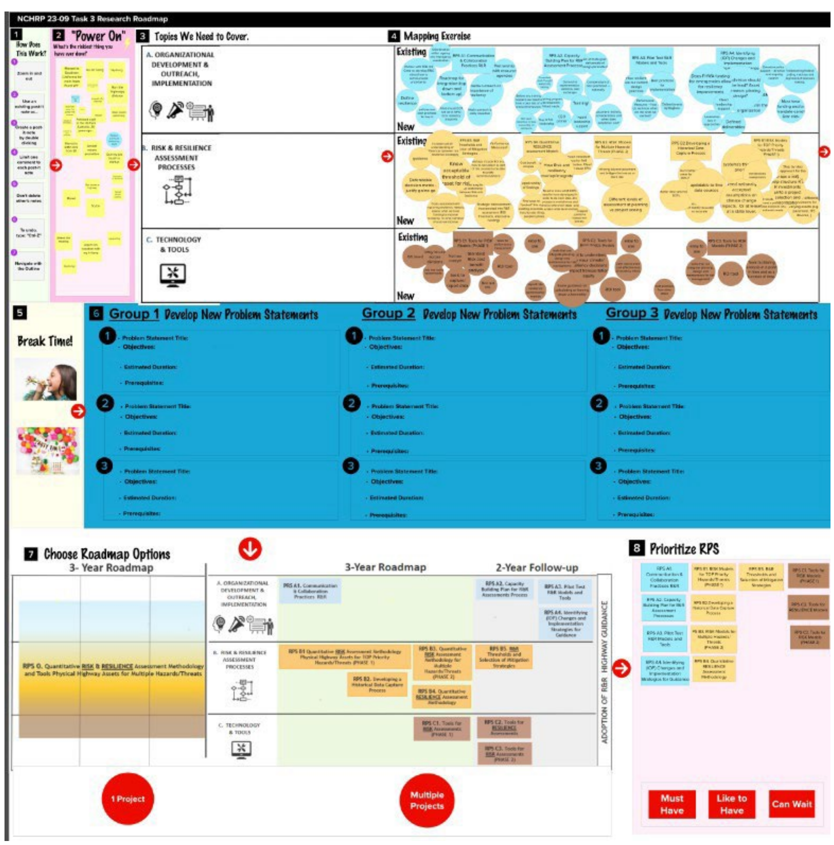

Figure 3. Mural interface

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The first two boards introduced the Mural interface to the participants. On the third board, “Topics We Need to Cover”, the participants were asked to pin virtual post-it-notes (Figure 4) by research “thematic lane” (see Figure 4). The three thematic lanes, derived from the gap analysis conducted during the research phase, are:

A. Organizational development and outreach, implementation
B. Risk and resilience assessment processes
C. Technology and tools.

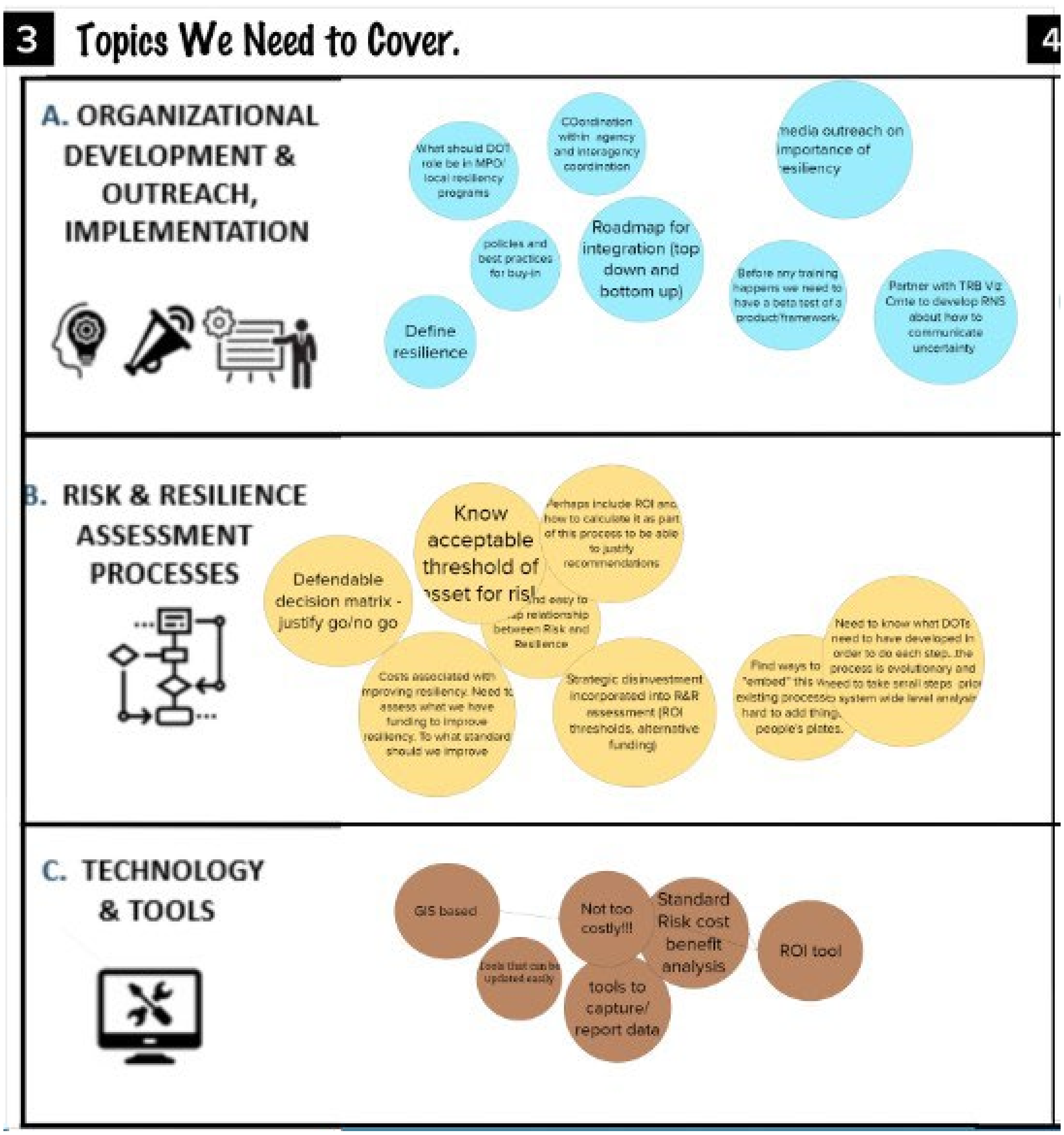

Figure 4. Activity 3 – Topics that need to be covered

Participants were instructed to jot down any topic they felt had not been addressed by the pre-established 12 research problem statements (see Table 1), using color-coded post-it-notes, and pinned to the appropriate thematic lane.

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Table 2. Pre-established RPS

Lane	Number	Title
A	RPS A1	Communication & Collaboration Practices R&R
	RPS A2	Capacity Building Plan for R&R Assessment Processes
	RPS A3	Pilot Test R&R Models and Tools
	RPS A4	Identifying (IOP) Changes and Implementation Strategies for Guidance
B	RPS B1	Risk Models for TOP Priority Hazards/Threats (PHASE 1)
	RPS B2	Developing a Historical Data Capture Process
	RPS B3	RISK Models for Multiple Hazards/Threats (PHASE 2)
	RPS B4	Quantitative RESILIENCE Assessment Methodology
	RPS B5	R&R Thresholds and Selection of Mitigation Strategies
C	RPS C1	Tools for RISK MODELS (PHASE 1)
	RPS C2	Tools for RESILIENCE Models
	RPS C3	Tools for RISK Models (PHASE 2)

The fourth board, "Mapping Exercise", required the participants to drag the post-it notes from board #3 to the Mapping Exercise board and place it next to the most closely related existing RPS (Figure 5). For example, the proposed topic, "partnership with resource agencies" was posted next to RPS A1, "Communication & Collaboration Practices". However, if the participants determined that a proposed topic did not align with any of the existing RPS, then the topic could be placed at the bottom of the appropriate swim lane, indicating that the new topic should be developed as a new RPS. Appendix A includes a table with the complete list of topics by RPS.

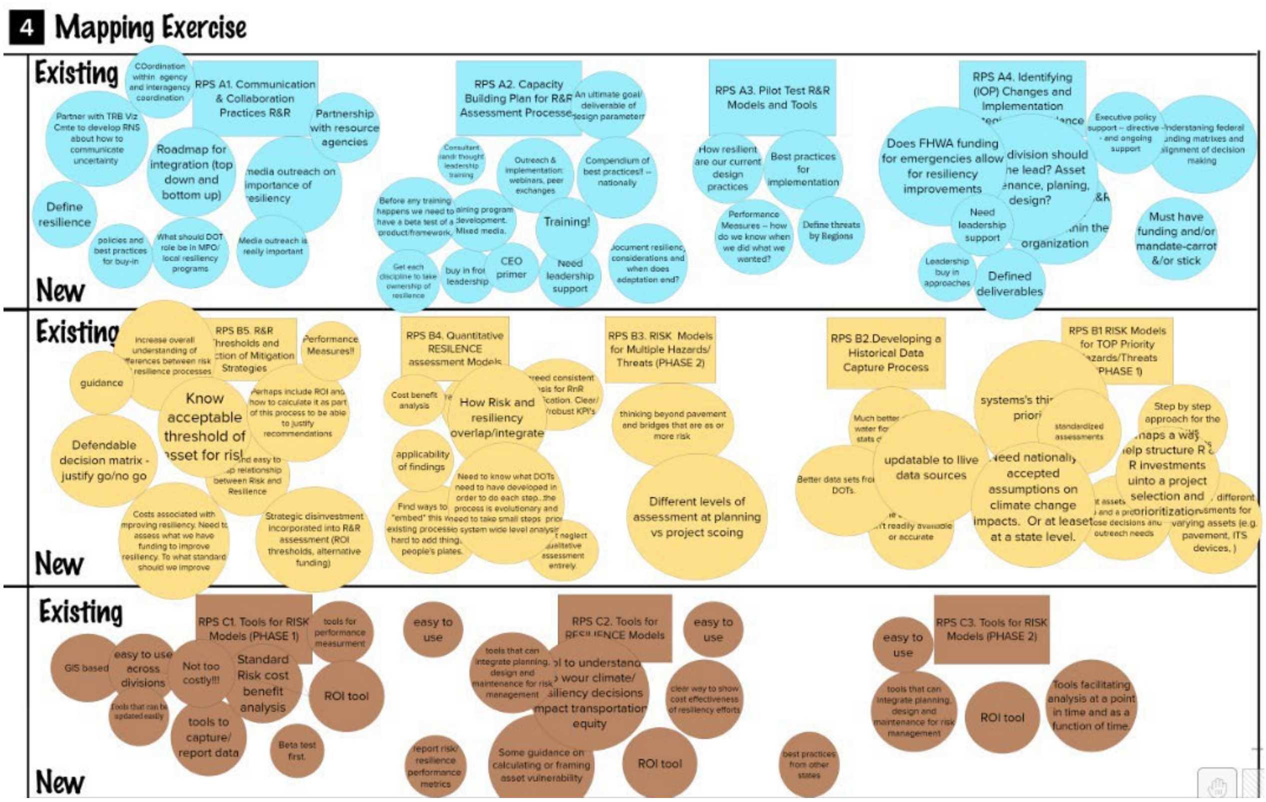

Figure 5. Mapping Exercise

The participants determined that almost all of the topics posted on the Mural did align with existing topics. Nine topics were not move to any of the existing RPS. The participants agreed that these 9, such as “keep it simple” and “customized to each discipline”, were common to all projects and were left in the “parking lot” (see Figure 6). The complete list of these 9 topics is included in the table in Appendix A.

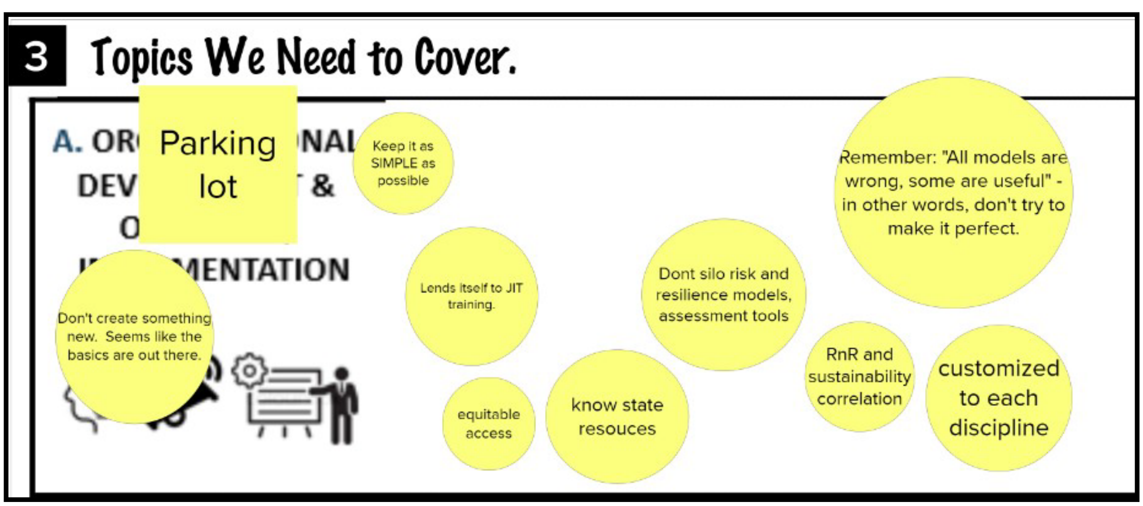

Figure 6. Parking Lot for General Topics

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One participant questioned whether incorporating strategic disinvestment into risk and resilience assessment could become a new RPS -- in other words, a method for agencies to determine if it was time to stop maintaining an under-used asset as well as a communication plan to address the politics of making such a decision. The research team explained that such a disinvestment strategy really belongs to RPS B5. Risk and Resilience Thresholds and Selection of Mitigation Strategies and offered to expand the description and objectives of RPS B5 to make sure this is covered.

Finally, the participants and research team came to the conclusion that no new RPS needed to be developed and Activity 6, “Develop New Problem Statements”, was skipped. The workshop advanced to the seventh activity, “Choose Roadmap Options” (see Figure 6). The participants had the option of selecting either Option 1, a 3-year roadmap where all of the tasks necessary to build a risk and resilience assessment standard are bundled into a single project, or Option 2, where the roadmap is subdivided into multiple projects over a 3-year time period plus a two-year follow-on for tool development and pilot study for validation.

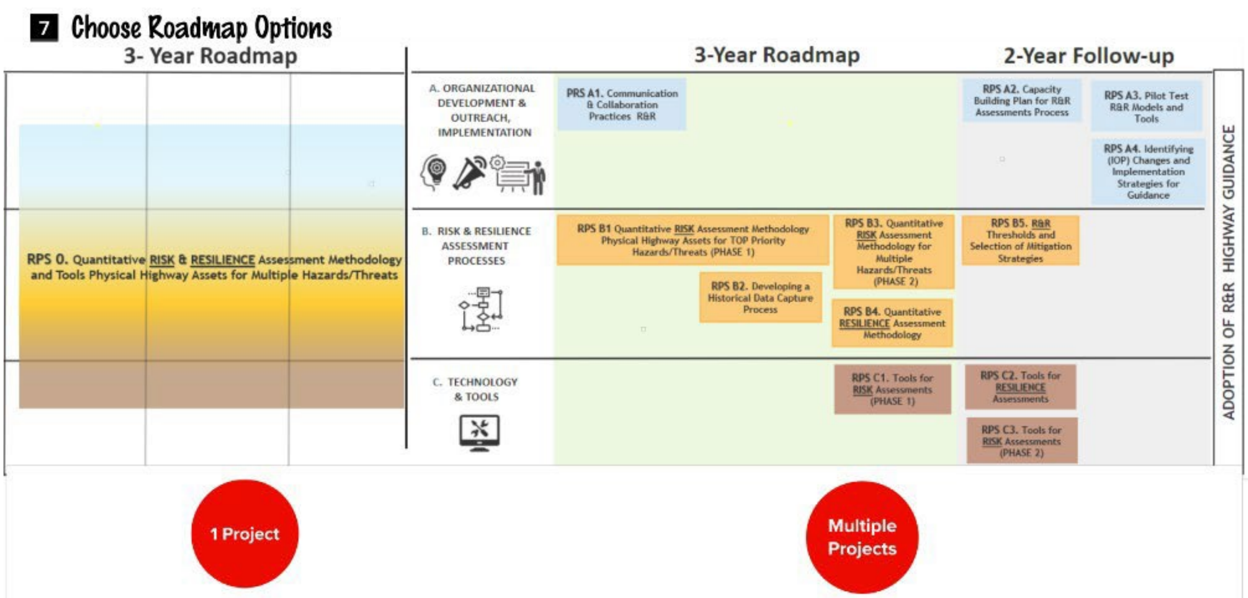

Figure 7. Roadmap Options

The research team explained the pros and cons of each option, as summarized in Table 2. One participant remarked that which option is appropriate depends on who will do the work – consultants, university researchers, or internal agency assets. One participant felt that a single project approach, Option 1, would be too much for any entity to handle and that it would be better to divide the project into bite-sized chunks, as in Option 2. Another asked if AASHTO Technical Support Services can do some of this work. Finally, one participant pointed out that due to the lengthy NCHRP

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approval and contracting process, any project proposed now will not likely be completed until at least four to 5 years in the future.

Table 3. Comparison of roadmap options 1 and 2

Option 1		Option 2	
+	−	+	−
Shorter delivery time.	Greater pressure to produce results quickly.	Projected divided into smaller, more easily managed pieces.	Longer delivery time.
Centralized effort and enhanced internal collaboration.	Higher project risk. Stuck with same project team for entire project.	Ensures prerequisites met for each step of the long-term effort. Potential for greater transparency	Separating different steps/phases into different projects requires each team to track and study other projects before launching.
Reduced redundancy in contracting process	Possibility of unforeseen cost overruns. Shorter timeline requires a larger team and budget.	Project teams selected based on expertise for each individual project.	Multiple projects and teams result in less continuity of effort.
Flexible, design-build approach. Project team can test and implement changes throughout the process.	Potential for less stability for each step/phase and less transparency.	R&R framework is fully fleshed out before tool development begins. Start and end points for each step are clearly defined, making it easier to measure progress.	Tool development pushed out to the end means less flexibility. Project team tasked to develop tools may be stuck with blueprint it does not agree with.

During the workshop the participants voiced a preference for Option 2, the multi-project approach. Due to technical difficulties and lack of time the participants were unable to conduct the final activity, "Prioritize RPS". As a remedy, the research team created an online survey with Wufoo.com. The actual survey form can be found in Appendix B. For each RPS, survey respondents were asked whether they felt a given RPS ***must*** be included in the 3-year roadmap, they ***would like*** to include the RPS, or the RPS ***can wait*** to be deferred to a later time. In addition, respondents had the option of entering what they thought the prerequisites for an RPS should and entering any additional comments relevant to each RPS. Most respondents chose not to suggest the prerequisites nor add additional comments. With 11 surveys completed, the majority (over 50%) indicated that RPS A3, B1, B3, B4, B5, C1, C2 and C3 are must haves. The survey respondents indicated that RPS A1, A2 and B2 are like-to-haves, while the results for RPS A4 were tied between must have and like-to-have (Figure 7).

	Must	Like	Can Wait
A1	18%	64%	18%
A2	45%	55%	0%
A3	55%	18%	27%
A4	36%	36%	27%
B1	82%	18%	0%
B2	27%	55%	18%
B3	55%	45%	0%
B4	64%	36%	0%
B5	64%	36%	0%
C1	73%	9%	18%
C2	64%	18%	18%
C3	55%	45%	0%

Figure 8. RPS Prioritization survey results

High-Level Takeaways

Several key points were emphasized and raised consistently by participants across topics:

- The participants agreed that the roadmap should be divided into multiple projects rather than a single, comprehensive project.
- The participants stressed preference for a 3-year roadmap to produce the most important deliverables as soon as possible, with a 2-year follow-on to produce needed but less critical features.
- Risk and resilience should not be completely siloed but treated as interrelated.
- The framework should be consistent and focus on highway assets.
- Tools and methodologies should be simple as possible and not too expensive. Do not try to make models perfect.
- Leadership buy-in is crucial, but this requires being able to demonstrate the benefits and costs of doing risk and resilience assessments.
- There are different levels of assessment: planning vs. project scoping.

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Appendix A: Table of suggested topics that should be covered by RPS

Swim Lane	RPS	Comment
A	A1. Communication & Collaboration Practices R&R	Coordination within agency and interagency coordination
		Partner with TRB Viz committee to develop RNS about how to communicate uncertainty
		Define resilience
		Roadmap for integration (top down and bottom up)
		policies and best practices for buy-in
		What should DOT role be in MPO/local resiliency programs
		Partnership with resource agencies
		media outreach on importance of resiliency
		Media outreach is really important
		Roadmap for integration (top down and bottom up)
A	A2. Capacity Building Plan for R&R Assessment Processes	An ultimate goal/deliverable of design parameters
		Consultant randr thought leadership training
		Outreach & implementation: webinars, peer exchanges
		Compendium of best practices!! -- nationally
		Before any training happens, we need to have a beta test of a product/framework.
		Training program development. Mixed media.
		Training!
		Get each discipline to take ownership of resilience
		buy in from leadership
		CEO Primer
		Need leadership support
		Document resiliency considerations and when does adaptation end?
A	A3. Pilot Test R&R Models and Tools	How resilient are our current design practices
		Best practices for implementation
		Performance Measures -- how do we know when we did what we wanted?
		Define threats by Regions
A	A4. Identifying (IOP) Changes and Implementation Strategies for Guidance	Does FHWA funding for emergencies allow for resiliency improvements
		which division should take the lead? Asset Maintenance, planning, design?
		Executive policy support -- directive -- and ongoing support

Swim Lane	RPS	Comment
		Understanding federal funding matrixes and alignment of decision making
		Need leadership support
		Strategies for enculturation of R&R lexicon and principals within the organization
		Must have funding and/or mandate-carrot &/or stick
		Leadership buy-in approaches
		Defined deliverables
B	B1. RISK Models for TOP Priority Hazards/Threats (PHASE 1)	systems' thinking and prioritizing
		standardized assessments
		Step by step approach for the various assessments
		Need nationally accepted assumptions on climate change impacts. Or at least at a state level.
		what assets can we let go and a process of those decisions and outreach needs
		Perhaps a way to help structure R & R investments into a project selection and prioritization framework
		ideas for different assessments for varying assets (e.g., pavement, ITS devices,)
B	B2.Developing a Historical Data Capture Process	Much better data on water flow -- stream stats doesn't work!
		Better data sets from our DOTs.
		updatable to live data sources
		Some data needed isn't readily available or accurate
B	RPS B3. RISK Models for Multiple Hazards/Threats (PHASE 2)	thinking beyond pavement and bridges that are as or more risk
		Different levels of assessment at planning vs project scoring
B	B4. Quantitative RESILENCE assessment Models	Cost benefit analysis
		How Risk and resiliency overlap/integrate
		A process framework which is flexible, but not overly so.
		Agreed consistent basis for R&R quantification. Clear/agreed/robust KPI's.
		applicability of findings
		Find ways to help "embed" this work in existing processes - it's hard to add things to people's plates.
		Need to know what DOTs need to have developed in order to do each step...the process is evolutionary and need to take small steps prior to system wide level analysis.

Swim Lane	RPS	Comment
		Don't neglect qualitative assessment entirely.
B	B5. R&R Thresholds and Selection of Mitigation Strategies	guidance
		increase overall understanding of differences between risk and resilience processes
		Performance Measures!!
		Defendable decision matrix - justify go/no go
		Know acceptable threshold of asset for risk
		Clear and easy to grasp relationship between Risk and Resilience
		Perhaps include ROI and how to calculate it as part of this process to be able to justify recommendations
		Costs associated with improving resiliency. Need to assess what we have funding to improve resiliency. To what standard should we improve
		Strategic disinvestment incorporated into R&R assessment (ROI thresholds, alternative funding)
C	C1. Tools for RISK Models (PHASE 1)	GIS based
		easy to use across divisions
		Not too costly!!!
		Standard Risk cost benefit analysis
		ROI tool
		Tools that can be updated easily
		tools to capture/report data
		Beta test first.
		Easy to use
C	C2. Tools for RESILIENCE Models	tools that can integrate planning, design and maintenance for risk management
		Tool to understand how our climate/resiliency decisions impact transportation equity
		clear way to show cost effectiveness of resiliency efforts
		report risk/resilience performance metrics
		Some guidance on calculating or framing asset vulnerability
		ROI tool
		best practices from other states
C	C3. Tools for RISK Models (PHASE 2)	easy to use
		tools that can integrate planning, design and maintenance for risk management
		ROI tool
		Tools facilitating analysis at a point in time and as a function of time.
"Parking Lot" – Common to all projects		Don't create something new. Seems like the basics are out there.
		Keep it as SIMPLE as possible

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Swim Lane	RPS	Comment
		Lends itself to JIT training.
		equitable access
		know state resources
		Don’t silo risk and resilience models, assessment tools
		R&R and sustainability correlation
		Remember: "All models are wrong, some are useful" - in other words, don't try to make it perfect.
		customized to each discipline

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Appendix B: Research Problem Statement Survey

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Research Problem Statement Survey Results

	Must	Like	Can Wait
A1. Communication and Collaboration Practices	18%	64%	18%
A2. Capacity Building Plan	45%	55%	0%
A3. Pilot Test R&R Models and Tools	55%	18%	27%
A4. Identifying (IOP) Changes & Implementation Strategies	36%	36%	27%
B1. RISK Assessment Methodologies Top Priority Hazards/Threats (PHASE 1)	82%	18%	0%
B2. Historical Data Capture Process	27%	55%	18%
B3. RISK Assessment Methodologies Other Hazards/Threats (PHASE 2)	55%	45%	0%
B4. RESILIENCE Assessment Methodologies	64%	36%	0%
B5. R&R Thresholds and Selection of Mitigation Strategies	64%	36%	0%
C1. Tools for RISK Models (PHASE 1)	73%	9%	18%
C2. Tools for RESILIENCE Models	64%	18%	18%
C3. Tools for RISK Models (PHASE 2)	55%	45%	0%

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Appendix C: PowerPoint Slide Show

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NCHRP

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PROGRAM

NCHRP 23-09

Scoping Study to Develop The Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis

Roadmap Validation Industry Workshop

September 22, 2021

Maria Pena, AEM
Vaishali Shah, AEM
Mara Campbell, Jacobs
Suseel Indrakanti, Cambridge Systematics

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Agenda

11:00 AM – Introductions Research Team & Participants

11:30 PM - Overview of Project and Workshop Objectives

11:40 PM – Overview of Roadmap Development

12:00 PM – Mural ACTIVITY: Warm up

12:05 PM – Mural ACTIVITY 1: Topics To Be Included in The Roadmap

12:30 PM – Mural ACTIVITY 2: Roadmap Mapping

12:50 PM – Break

1:00 PM – Mural ACTIVITY 3: Develop NEW Research problem Statements (RPS)

1:20 PM – Mural ACTIVITY 4: Discussion of Roadmap Option

1:35 PM – Mural ACTIVITY 5: Prioritization of Research Topics

1:55 PM – Questions and Final Remarks

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Introductions
Core Research Team

Maria Pena
AEM

Vaishali Shah
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Cambridge Systematics

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Project Objectives

Conduct a scoping study for an all-hazards risk and resilience analysis framework of transportation assets.

The scoping study will:

1. **Develop comprehensive and consistent terminology** for risk- and resilience-related terms for transportation agency use.

2. **Define an industry-informed research roadmap** to develop a framework for a quantitative all-hazards risk and resilience analysis of highway assets.

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Project Overview

- **Phase 1: Information Gathering**
  - ✓ Task 1 a. Risk and Resilience Glossary of Terms
  - ✓ Task 1b. State of Practice Review
  - ✓ Task 1c. Gap Assessment of State of Practice
  - ✓ Task 2. Stakeholder Engagements

Phase 2: Product Development

- ✓ Task 3a. Roadmap
- ✓ Task 3c. Research Problem Statements (RPS)
- Task 3b. Industry Workshop for Roadmap validation
- Task 4. Finalized Roadmap and RPS

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Workshop Objectives

1. Validate Research Topics and Problem Statements (RPS)

2. Validate Research Roadmap

- **Roadmap includes:**
  - Data gathering and state of practice review
  - Communication and collaboration strategies
  - Risk and Resilience models and tools development
  - Capacity building
  - Adoption and implementation
  - Pilot testing/validation

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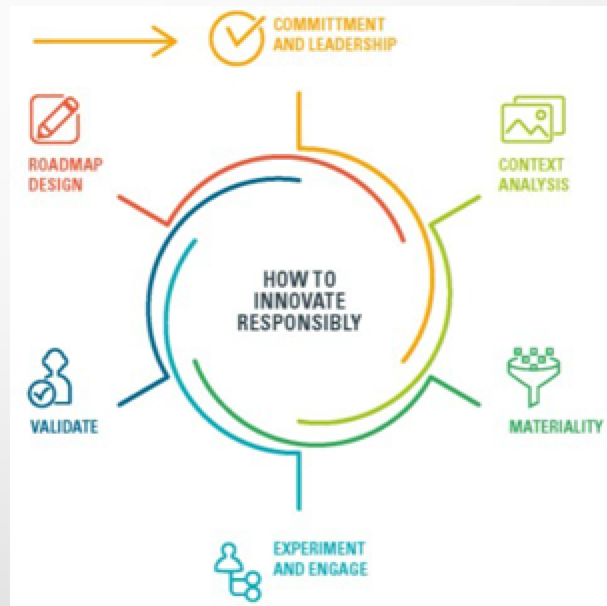
Task 3. Research Roadmap and Problem Statements Development

Recipe for a Tactical Roadmap

- Mission
- Goals
- Framework
- Duration
- Thematic lanes
- Candidate research activities

by thematic lane



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Roadmap Development: Mission

"Our mission is to create an **efficient guidance** for state DOTs to implement consistent **physical transportation highway asset** risk and resilience processes within and among organizations for improved sustainability"

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Roadmap Development: Goals

1. Identify **organizational development and outreach** when implementing risk and resiliency "Guidance."
2. Define a **consistent framework** for risk and resilience assessment that identifies core processes and methods.
3. To identify candidate **research activities** that advance key Roadmap elements.
4. To identify **tools** to assist with risk and resilience assessments that align with the "Guidance."
5. To identify **technical skillsets and training** to facilitate the conduct of risk and resiliency analyses.

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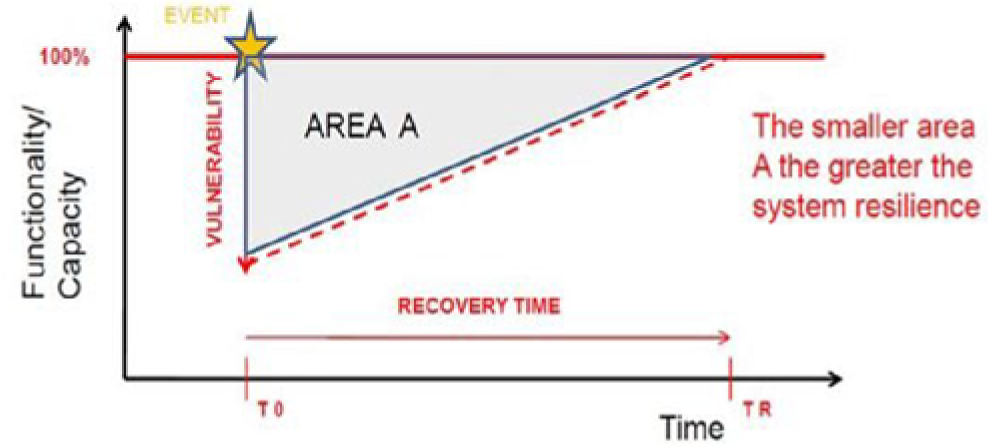
Relationship Between Risk and Resilience

Risk Definition: "The potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and associated consequences."

– AASHTO, 2017

Risk metric examples: monetized ($), low-medium-high, 1 - 2 - 3, etc.



Dr James Kimmance, Infrastructure Risk & Resilience: BCI Workshop, Bristol 2010

Resilience: "the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to and recover rapidly from disruptions."

– FHWA Order 5520, 2014

Resilience metrics: e.g., recovery time, productivity loss, low-medium-high

"Natural and human-induced risks affect system resilience, either by threatening or enhancing resilience"

– NCHRP 20-59(55) Resilience a DOT Imperative

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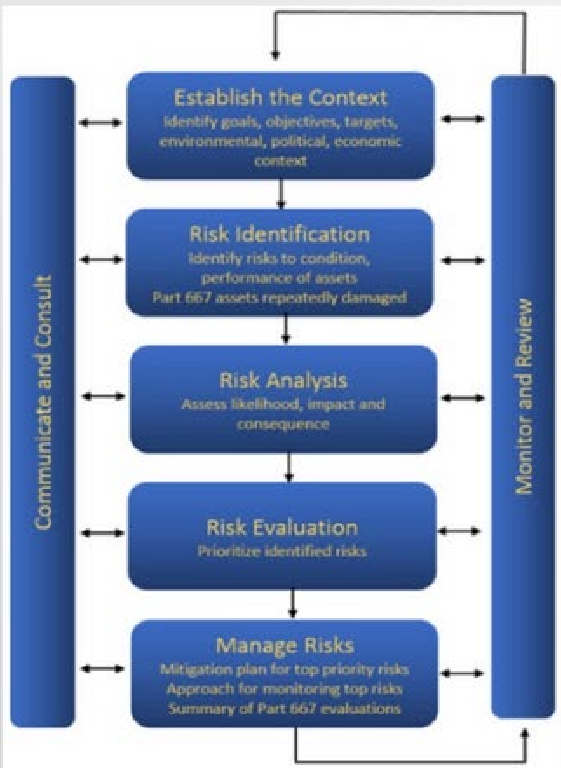
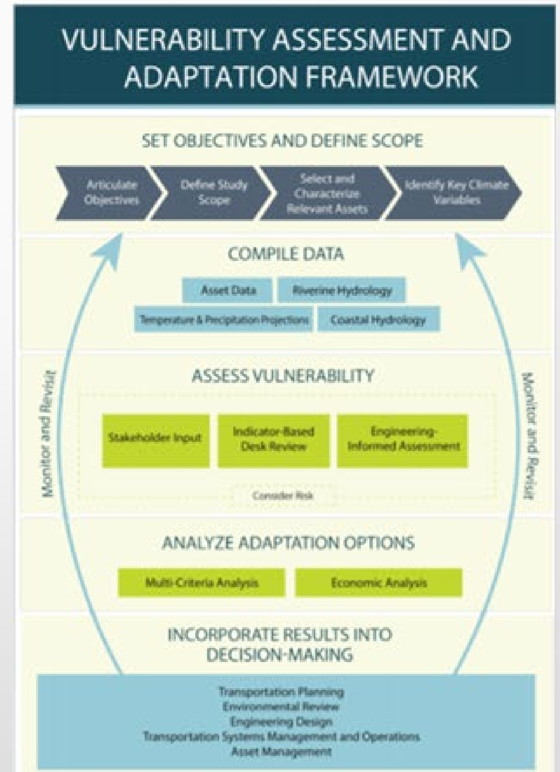
Risk and Resilience Frameworks

FHWA Final Rule Framework (derived from ISO 3100)



CDOT Guidebook Parallels Water and Wastewater Framework

FHWA VAST Framework



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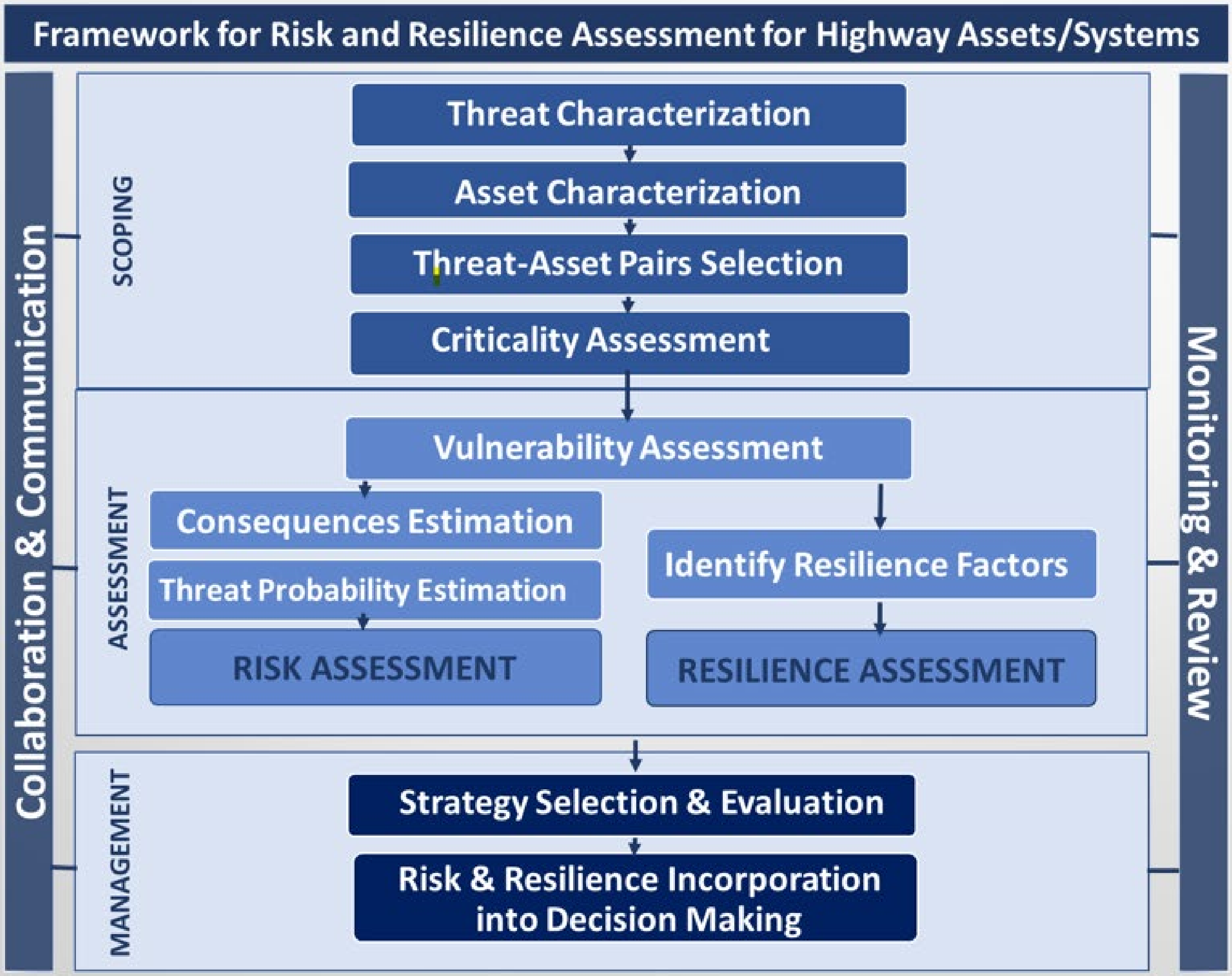
Roadmap Development: Framework



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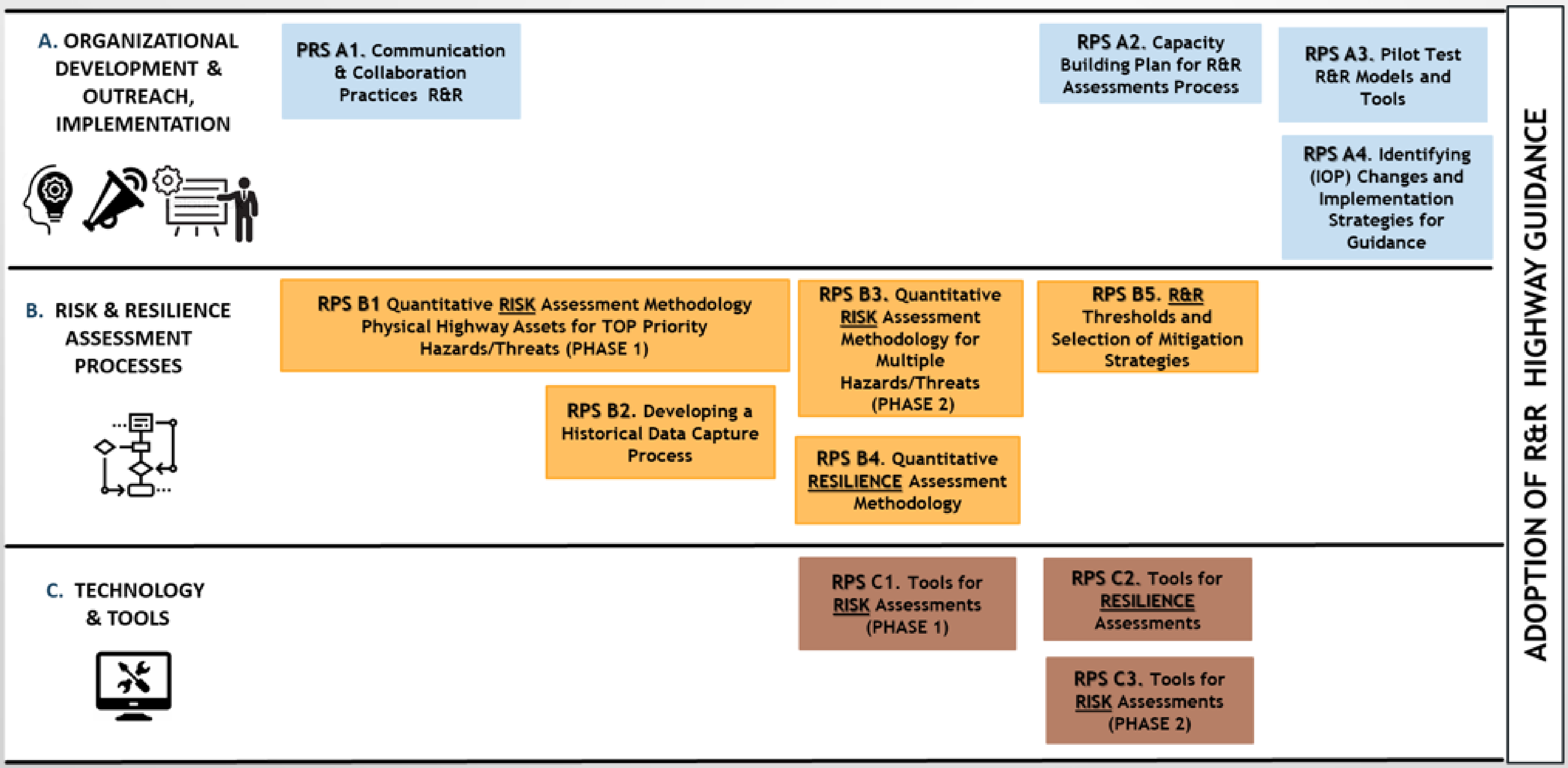
Roadmap Development:

Thematic Lanes and Research Projects



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Mural Activities

- **Activity 1:** Brainstorming of topics to be covered in the Roadmap by Thematic Lane.
- **Activity 2:** Mapping Roadmap topics to existing RPS.
- **Activity 3** Development of New Research Problem Statements (RPS) based on NEW topics from Activity 3.
- **Activity 4:** Discussion of Roadmap options.
- **Activity 5:** Selection of priority topics for Roadmap.

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Mural Exercises Tips

- If you have **2 monitors**, please use one for accessing the Mural link and activities and the other one to see presentation slides.
- **Use the link provided** on the Chat to access Mural.
- Access the Mural activities shown on the link, **NOT** on the research team's presentation.

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Final Remarks

- Recap Meeting and Outcomes
  - Brainstorm research topics to include in Roadmap
  - Develop NEW Research Problem Statements (RPS)
  - Discussion of Roadmap options
  - Prioritization of research topics for a 3-yr Roadmap
- Next Steps
  - Revise and finalize Roadmap and Research Problem Statements (RPS)
  - Provide final report

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP 23-09

Scoping Study to Develop The Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis

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APPENDIX F – IMPLEMENTATION PLAN

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Project No. NCHRP 23-09

Scoping Study to Develop the Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis

IMPLEMENTATION PLAN AND ADDITIONAL RESEARCH PRIORITIES

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
of
The National Academies of Sciences, Engineering, and Medicine

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April 2022

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NCHRP 23-09

Scoping Study to Develop the Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis

NCHRP NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Technical Memorandum

NCHRP 23-09 Implementation Plan and Additional Research Priorities

Prepared by AEM Corporation

April 2022

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Introduction

The primary objectives of the NCHRP 23-09 Project, *Scoping Study to Develop the Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis*, were to (1) develop a comprehensive and consistent set of risk and resilience related terminology, and to (2) formulate a research roadmap to establish a framework that supports quantitative assessments of all-hazard risk and resilience (R&R) for State and local transportation agencies. The NCHRP 23-09 Research Project in its execution will facilitate both of these objectives. This document identifies mechanisms and channels of how this research can be communicated and implemented moving forward. It will identify:

- Actionable recommendations
- Opportunities to implement
- The need and priority for specific additional research concepts
- Immediate next steps to broadcast results following NCHRP 23-09 research efforts

This document recognizes planned and ongoing NCHRP efforts. It will also identify research opportunities that may be pursued by NCHRP, AASHTO, and State Planning and Research (SPR) grants, pooled fund studies, University Transportation Centers, and other state-level research programs.

In addition, the findings of this research should be shared within the transportation industry. It is recommended this information is discussed via presentations to multiple AASHTO committees and subcommittees and councils interested in this topic, as well as with FHWA. Because of the nature of this research, it is also recommended the findings within this research be shared as a lectern session during the 2023 Annual TRB Meeting.

Actionable Findings and Recommendations

In order for additional research to be useful for transportation agencies, it should speak to actionable findings and recommendations. Analytical risk assessment methods to support risk-based asset management processes are the best approach to support an all-hazards risk and resilience analysis for the highway system. The research made actionable recommendations through 3 major roadmap themes all the RPSs were created to help address:

- **Organizational Development, Outreach, and Implementation** | Development of organizational work to start creating the R&R framework/manual as well as all the outreach and communication strategies and tasks for producing the framework/manual. In addition, it also will include the implementation strategies for the successful adoption of the framework, and the activities to develop and maintain robust R&R training and capacity building strategies.
- **Risk and Resilience (R&R) Assessment Processes** | Development of processes to identify the most critical highway infrastructure, threats to their system, assess the vulnerability of their system and conduct a complete risk and resilience analysis. In addition, transportation agencies need a comprehensive data collection plan to compile threat, asset, and event data to support and validate their risk and resilience assessments.

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- **Technology and Tools** | Identify or establish the appropriate tools, to facilitate the incorporation of R&R methodologies within the different agency areas.

Opportunities to Implement

The research will likely be most helpful to agencies that need to adopt a Risk and Resilience Highway Framework to conduct an All-Hazards Risk and Resilience (R&R) Assessment. These opportunities may include:

- Development of Research Problem Statements (RPSs) that will address the types of activities needed to support the development and adoption of an all-hazards risk and resilience analysis. These have been included in the Final Report and should be considered for funding moving forward. This also includes the prioritization and customization of specific needs within the transportation community, due to agency maturity or other specific needs.

- Development of an outreach plan that describes channels, venues, and professional organizations that will potentially assist in sharing and marketing the research products which include the summaries of the industry workshop, guidance, and Research Problem Statements. The following should be considered:

  - **AASHTO committees:** The AASHTO structure is such that it affects and supports all state DOTs. The different committees within AASHTO can effectively garner support to move these research problem statements (RPSs) forward. We specifically recommend enhancing collaboration with the following AASHTO committees and subcommittees: Committee on Performance-Based Management (CPBM), Subcommittee on Risk Management, and the Committee on Transportation System Security and Resilience (TSSR). There are other committees and councils within AASHTO that could benefit from this research such as the Committee on Planning as well as the Highways and Streets Council.

    - **TRB committees:** TRB is comprised of many standing committees within its Technical Activities Division that are interested in and support research on the topic of resiliency. TRB is comprised of academia, consultants, government officials, and other transportation professionals. These standing committees can help to share the findings:

      - AJE00 – Executive Management Issues Section
        - AJE10 – Strategic Management
        - AJE15 – Workforce Development and Organizational Excellence
        - AJE20 – Performance Management
        - AJE30 – Asset Management
        - AJE40 – Public Engagement and Communications
        - AJE70 – Data for decision making

      - AMR00 – Transportation System Resilience Section
        - AMR10 – Critical Infrastructure Protection
        - AMR20 – Disaster Response, Emergency Evacuations, and Business Continuity
        - AMR30 – Transportation for National Defense
        - AMR40 – Systems, Enterprise, and Cyber Resilience
        - AMR50 – Extreme Weather and Climate Change Adaptation

      - AEP10 – Transportation Planning Policy and Process

      - AT040 – Subcommittee on Risk Management

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- **State DOTs:** Each state DOT has interested staff and teams focused on resiliency. The products and results from this research should be forwarded to each state DOT for further consideration.

- **FHWA:** Multiple resilience efforts have been initiated and conducted by FHWA. It is key to establish communication and collaboration strategies among TRB, AASHTO, state DOTs, and FHWA to streamline and optimize the development of R&R methodologies and tools, as well as to emphasize the importance and facilitate the implementation of the R&R roadmap products.

- Development of a Communications Plan that describes goals, objectives, target audience, channels, tools, and key themes to educate the value of research products. Within the communication plans, various types of communication methods such as newsletters, Podcasts, and other media are criterial to sharing the information that was gathered during this research.

- Development and dissemination of the final Research Roadmap to advance the preparedness of the transportation sector for emerging threats and increase the resilience of the transportation system.

Need and Priority for Additional Research Concepts

Research that builds on NCHRP 23-09 speaks to both the actionable findings of this project and an agencies' most effective implementation opportunities. The RPSs identified in this research project should be contemplated moving forward and are organized into four categories:

- **Time-Sensitive |** These concepts may be useful for the 2022 NCHRP round and as such may need to be submitted in 2022 or 2023.

- **Sequence Needed for Success |** These concepts build directly from the findings of this research and have similar approaches and lines of inquiry.

- **High-Value Assistance |** These concepts were suggested or inspired by participants in 23-09 workshops as well as the project panel and could bring significant benefits to agencies in the areas discussed in this work.

- **Ongoing Efforts |** These concepts build upon prior or current research efforts that relate to the areas discussed in this work.

Immediate Next Steps

The research team recommends the next steps:

- *Formal adoption and approval of the Glossary of Terms and the RPS contained within this research*

- *Identify champions (within the AASHTO committee structure) and map out the sequence for necessary funding through NCHRP and/or other funding sources |*

- *Create a team that initiates the implementation and communication plan and continues to elevate it until all RPS are underway.*

Approval of the research or adoption/integration of any of the RPS in this document would be a propitious next step for NCHRP and other researchers in assisting agencies in putting the research into practice and realizing its worth.

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Conclusions

The R&R research roadmap and framework aim to guide the development of the necessary research to achieve the adoption and implementation of the R&R framework/manual. It is important to highlight the key elements or activities to ensure successful implementation:

- Establish a working group or task force to oversee the execution of the proposed R&R roadmap and products (e.g., R&R Highway Framework/Manual)

- Enhance communication and collaboration among the transportation industry including TRB, AASHTO, state DOTs, and FHWA to ensure and streamline the successful development and implementation of the R&R framework/manual and associated products.

- Enhance continuous communication and collaboration among the principal investigators (PIs) of the different projects on the proposed research roadmap to ensure consistency and continuity of the projects.

- Ensure past and ongoing research in the area of risk and resilience is streamlined and incorporated into the development of the proposed roadmap products to reduce efforts, duplication, and improve consistency.

- It is important to recognize that due to the long-term timeframe of the roadmap, it should be an interactive process where communication with the different parties involved in the projects may need to respond to continuous feedback.

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APPENDIX G – COMMUNICATION MATERIAL

NCHRP 23-09 Scoping Study to Develop the Basis for a Highway Framework to Conduct an All-Hazards Risk and Resilience Analysis

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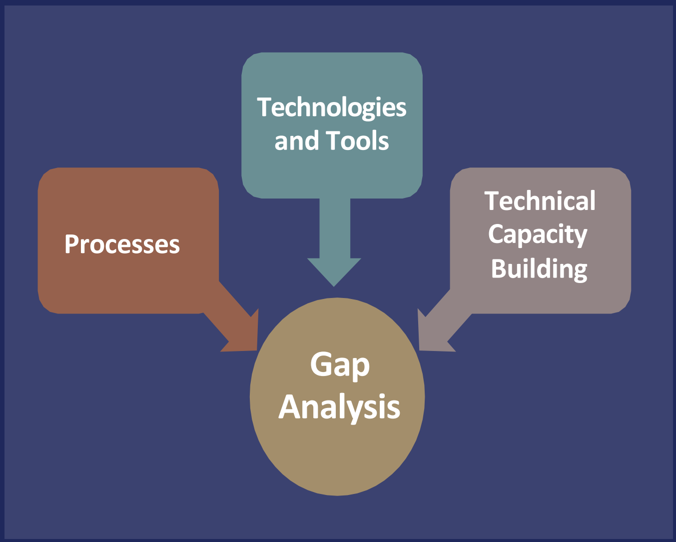
Project Background

Transportation owners and operators are responsible for the highway system and the delivery of a range of services and functions through the management of that system. There are inherent risks involved with the management of these systems, notwithstanding aging infrastructure, and fiscally constrained resources.

Many agencies are moving toward performance-based resource allocation while simultaneously recognizing risks that may undermine their strategic goals. As these risks affect every component of a highway system, accurately accounting for and addressing these risks within a highway agency's enterprise-wide management program is the goal that currently lacks analysis tools. In addition, state DOTs are required to develop a process for quantifying annual risk to increase their system resilience as part of the Infrastructure Investment and Jobs Act (IIJA) also known as the Bipartisan Infrastructure Bill (BIL).

The purpose of this study is to establish an understanding of the research required to establish quantitative methods to support all-hazards risk and resilience analysis for the highway system.



Gap Analysis

Project Accomplishments

Glossary of Terms

The research team compiled a glossary with 213 terms and definitions from 91 sources. Definitions were derived from transportation sectors such as FHWA, AASHTO, and TRB and selected through the lens of crafting a standard for risk and resilience analysis.

Gap Analysis

A comprehensive review of the state of practice revealed gaps that can be organized according to three categories: 1) Processes, 2) Technologies and Tools, and 3) Technical Capacity Building.

- **Processes**, including institutional and DOT business processes that are used to develop risk and resilience (R&R) assessments.
- **Technologies and Tools,** which are used to develop and support the R&R assessments.
- **Technical Capacity Building,** including gaps in areas such as educational support, staff training, and skill development.

The Risk and Resilience (R&R) Framework

As part of this project, a framework for conducting a quantitative R&R assessment was developed based on multiple existent and proven R&R frameworks such as FHWA Vulnerability Assessment and Adaptation Framework, ISO 3100, and RAMCAP frameworks among others. The provided framework:

- Followed the core bases for conducting quantitative R&R assessment.
- Provides flexible sequencing of steps.
- Provides linkages to practice integration and decision making.
- Served as the bases to create the research Roadmap and Research Problem Statements (RPSs).

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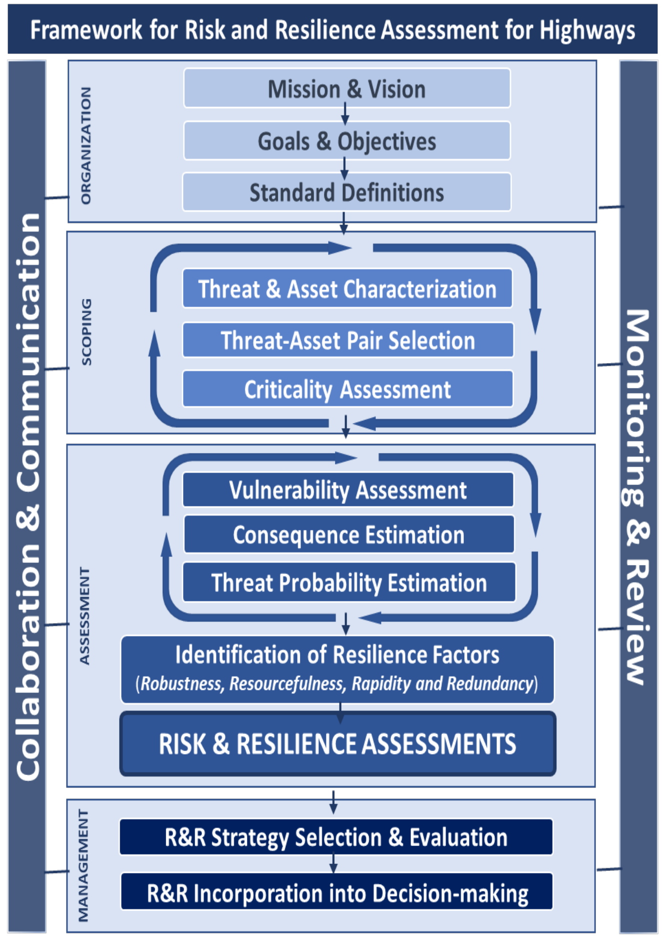
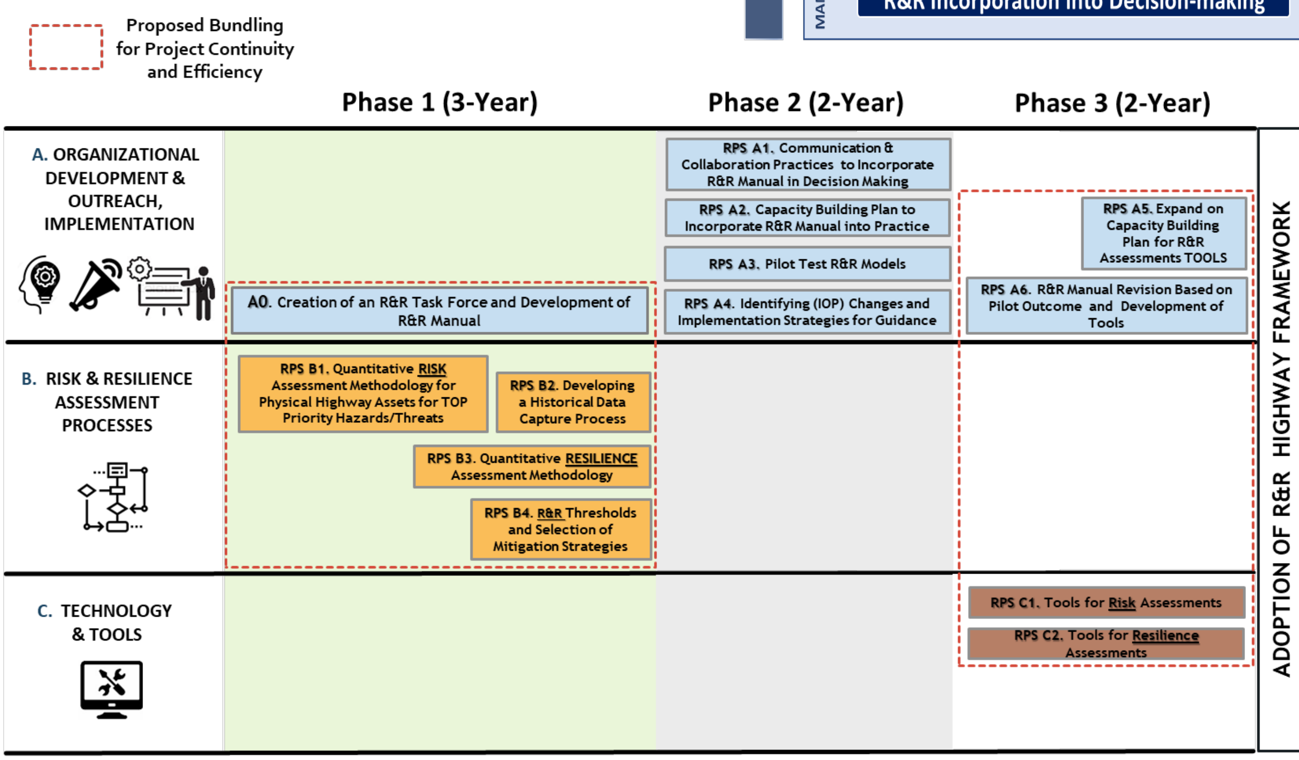
Twelve RPSs were developed to cover all the steps of the R&R Framework. The RPSs were divided into three main thematic lanes that built the research Roadmap
A) Organizational Development, Outreach, and Implementation, B) R&R Assessment Process, and C) Technology and Tools as shown in the figure below.



The Benefits for DOTs

- Provides a research Roadmap to develop a comprehensive manual, tools, training, and implementation guidance for quantitative R&R assessment that satisfies the requirements of the new Infrastructure Investment and Jobs Act (IIJA)/BIL.
- Lays the framework for a consistent approach to R&R assessments, conduct economic analysis, project prioritization, and asst and performance management for the more efficient use of available funds.
- Advances the preparedness of the transportation sector for emerging threats, including extreme weather, climate change, and cyber.
- Enables state DOTs to communicate risk and make the business case for resilience investments in the face of uncertainty.



Expected Outcomes: **Phase 1:** R&R framework/manual; **Phase 2**: Validation of the framework, training, and implementation; **Phase 3:** R&R tools and revised R&R manual

Research Roadmap and Research Problem Statements (RPS)

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Project No. NCHRP 23-09

Scoping Study to Develop the Basis for a Highway Standard to Conduct an All-Hazards Risk and Resilience Analysis

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
of
The National Academies of Sciences, Engineering, and Medicine

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April 2022

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NCHRP NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Research Summary Presentation

NCHRP 23-09: SCOPING STUDY TO DEVELOP THE BASIS FOR A HIGHWAY STANDARD TO CONDUCT AN ALL-HAZARDS RISK AND RESILIENCE ANALYSIS

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Outline

- Project Objectives
- Tasks and Structure
- Deliverables and Outcomes
- Key Takeaways and Benefits to DOTs
- Next Steps

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Project Objectives

Conduct a scoping study for an all-hazards risk and resilience analysis framework of transportation assets.

The scoping study developed:

1. **A comprehensive and consistent terminology** for risk- and resilience-related terms for transportation agency use.
2. **An industry-informed research roadmap** to develop a framework for a quantitative all-hazards risk and resilience analysis of highway assets.

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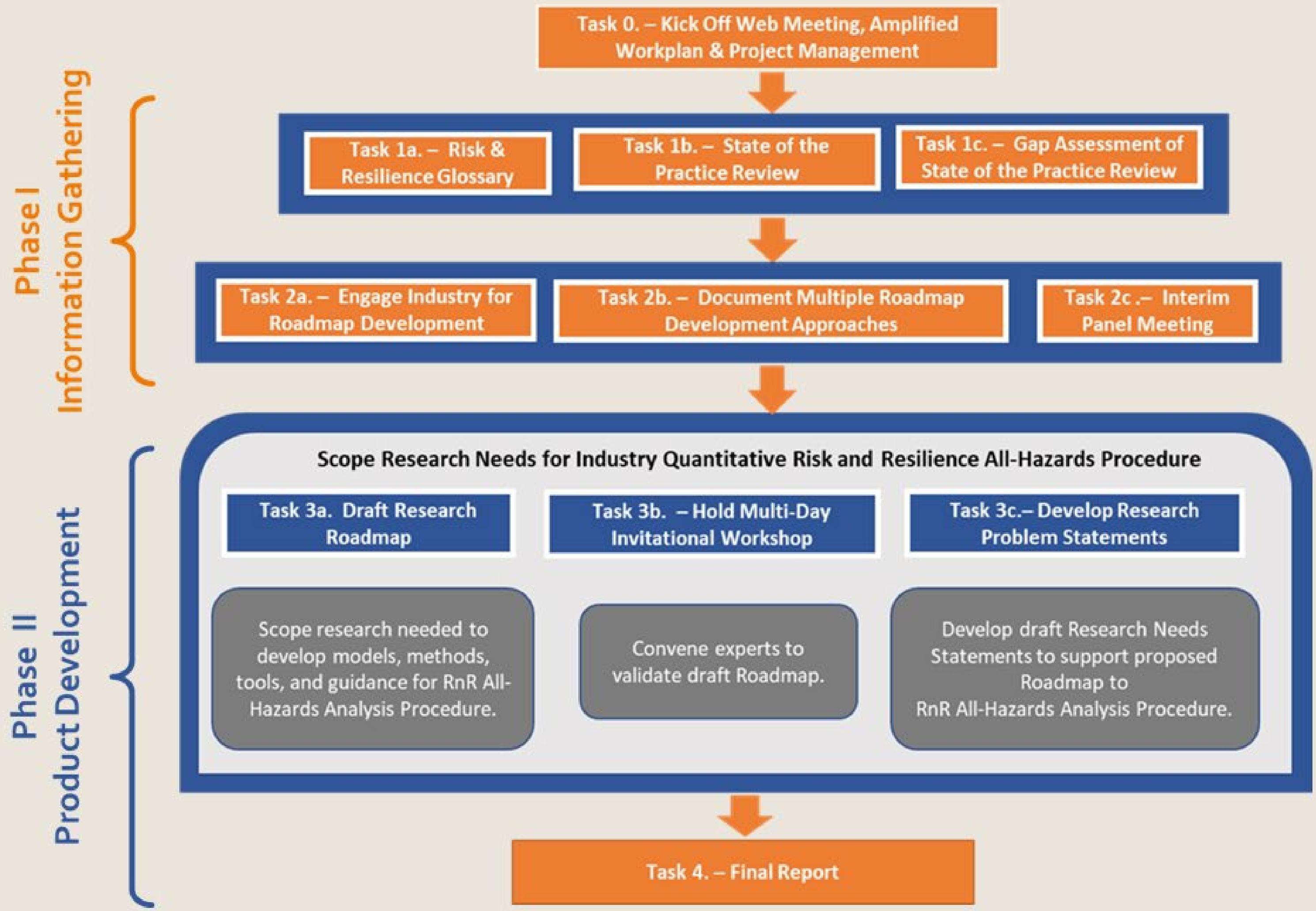
Project Structure and Tasks



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Risk and Resilience Glossary of Terms Development

- To serve as a comprehensive and consistent terminology for risk- and resilience-related terms for transportation agency use.
- Glossary with 213 terms and definitions from 91 sources.
  - Terms selected through the lens of crafting a R&R Highway Standard.
  - Limited to 3 definitions per term.
  - Definitions derived from transportation sectors sources such as FHWA, AASHTO and TRB.

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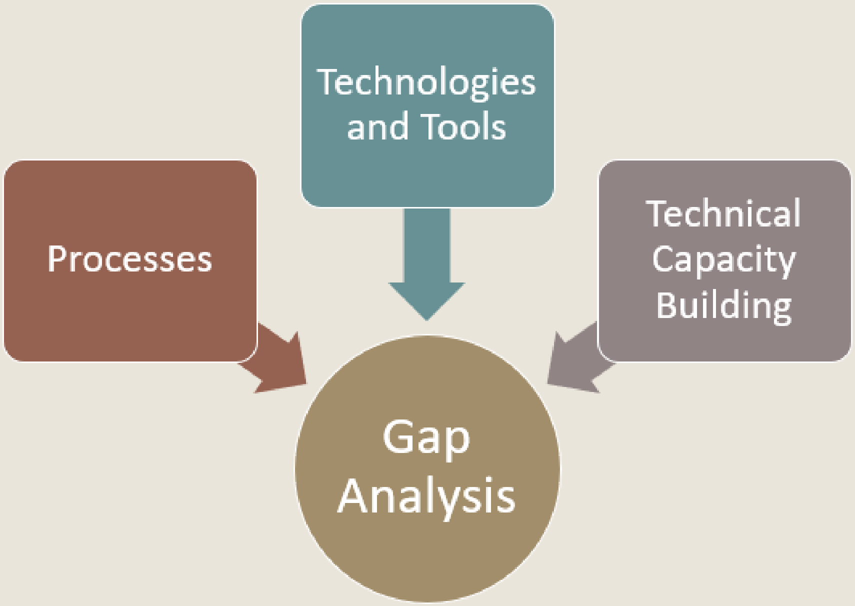
Gap Analysis of State Of Practice Assessment

- State of practice – basis for gap analysis
  - Barriers and limitations and lessons learned.
- Grouped into three categories
  - **Processes**, including institutional and DOT business processes that are used to develop risk and resilience assessments.
  - **Technologies and Tools**, which are used to develop and support assessments.
  - **Technical Capacity Building**, including gaps in areas such as educational support, staff training, and skill development.



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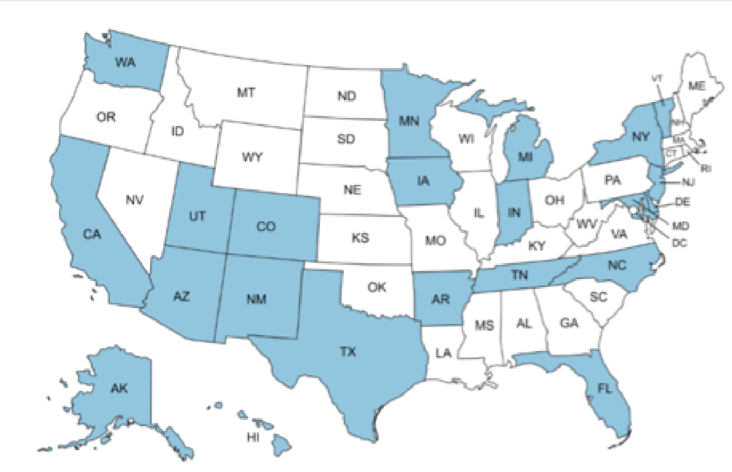
Stakeholder Engagement for Roadmap **Development**

- Two Virtual Industry Workshops
  - Organized in April and March 2021.
  - Total of 55 participants
  - 21 states represented along with State DOTs, US DOT, AASHTO, FHWA, local agencies, academia, and the private sector.
- Validate Gap Analysis
- Provide Inputs to Roadmap Development
- Seek Involvement for Roadmap and Research Problem Statements Development.



States represented in industry workshops

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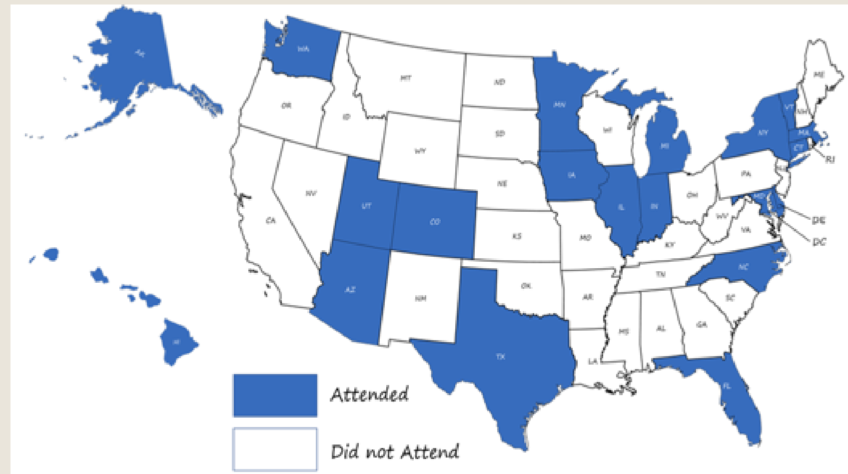
Industry Workshop for R&R Framework and Roadmap **Validation**

- One Industry Workshop
  - Conducted September 2021
  - 35 participants- including panel members; representatives from 20 states, FHWA, TRB, and academia
- Review R&R framework development and enhancement
- Provide a review of Research Problem Statements (RPS)
- Discuss roadmap priorities, synergies, and dependencies
  - Project sequencing and bundling



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R&R Research Roadmap

Mission: “To create an **efficient guidance** for state DOTs to implement consistent **physical transportation highway asset** risk and resilience processes within and among organizations for improved sustainability”

Three-Phase Roadmap (7-years)

- Phase 1 – Development of “Highway Risk & Resilience Manual”
  - Duration: 3 years
  - Estimated Cost: ~$3.5 million
  - 4 Research Problem Statements (RPS)
- Phase 2 – Pilot test “Highway Risk & Resilience Manual” and implementation
  - Duration: 2 years
  - Estimated Cost: ~$2 million
  - 4 Research Problem Statements (RPS)
- Phase 3 – Development of tools
  - Duration: 2 years
  - Estimated Cost: ~$1.5 million
  - 4 Research Problem Statements (RPS)

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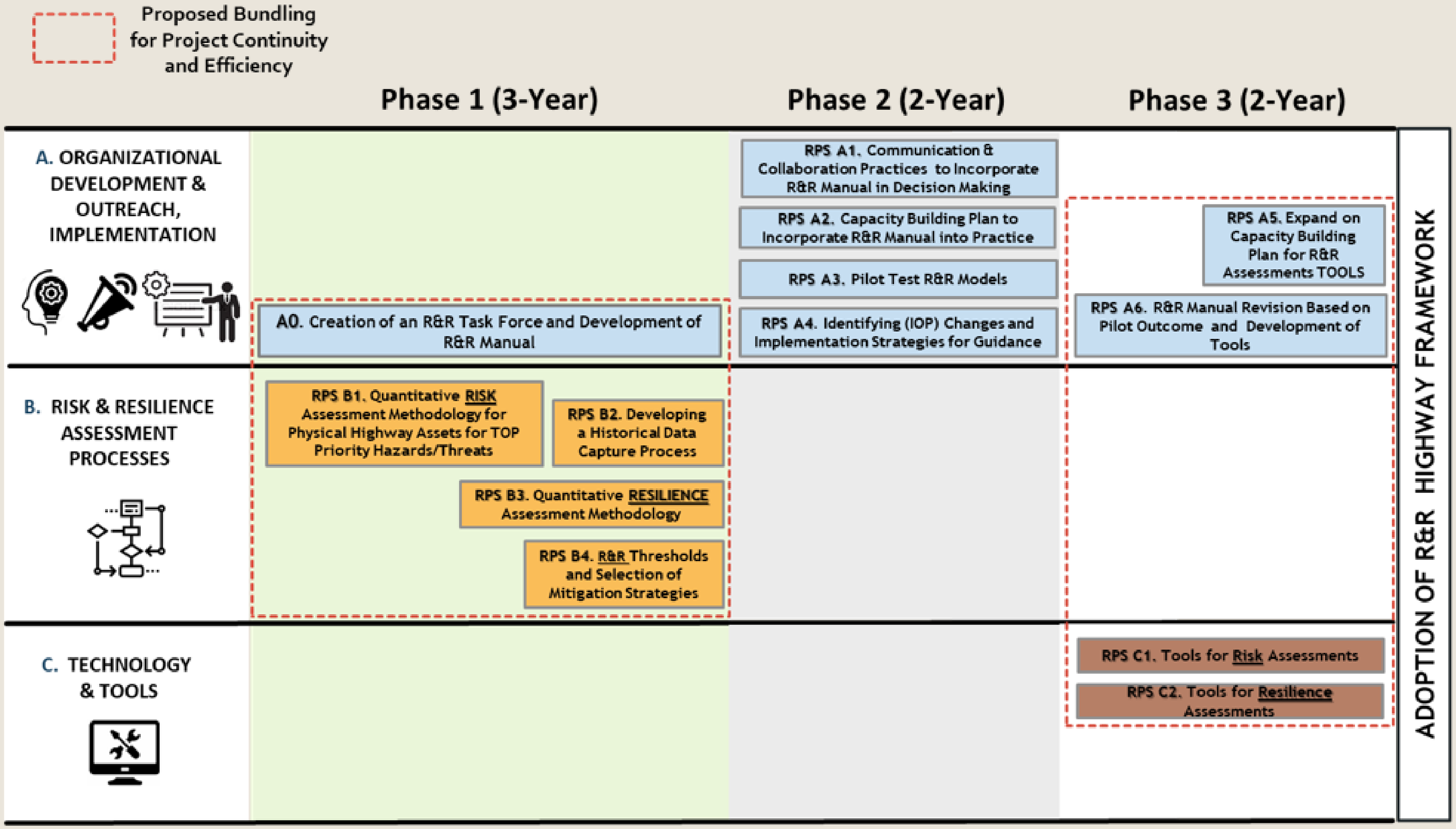
Roadmap Sequencing and Project Bundling



Expected Outcomes: **Phase 1:** R&R framework/manual; **Phase 2:** Models validation, training, and implementation; **Phase 3:** R&R tools and revised R&R manual

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Thematic Lane	Research Problem Statement
Lane A. Organizational Development and Outreach, and Implementation	**RPS A1.** Creating Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management.
	RPS A2. Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency (R&R) Assessments at Transportation Agencies.
	RPS A3. Pilot Testing the Highway Risk and Resilience (R&R) Manual and Interface with Existing Asset Management Systems and Other Agency Functions
	RPS A4. Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of the Highway R&R Manual.
	RPS A5. Enhancing the Capacity Building and Implementation Plans to Incorporate Highway Risk and Resilience Manual and Tools
	RPS A6. Revising the Highway Risk and Resilience Manual
Lane B. Risk and Resilience Assessment Processes	**RPS B1.** Establishing a Quantitative Multi-hazard **Risk** Assessment Methodology for Highway Assets
	RPS B2. Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments.
	RPS B3. Establishing a Quantitative **Resilience** Assessment Methodology for Transportation Highway Assets
	RPS B4. Establishing Considerations for Defining Risk and Resilience Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure
Lane C. Technology and Tools	**RPS C1.** Identifying and Developing Analytical Tools to Conduct **Risk** Assessments for Highway Assets.
	RPS C2. Identifying and Developing Analytical Tools to Conduct **Resilience** Assessments for Highway Assets.

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Roadmap Phase	Research Problem Statement
Phase 1: Development of R&R framework/manual	**RPS B1.** Establishing a Quantitative Multi-hazard **Risk** Assessment Methodology for Highway Assets
	RPS B2. Developing a Historical Data Capture Process and System for Risk & Resilience (R&R) Assessments.
	RPS B3. Establishing a Quantitative **Resilience** Assessment Methodology for Transportation Highway Assets
	RPS B4. Establishing Considerations for Defining Risk and Resilience Thresholds and Methodologies for the Selection of Risk Mitigation and Resilience Improvement Strategies for Highway Infrastructure
Phase 2: Models validation, training, and implementation	**RPS A1.** Creating Internal and External Agency Communication and Collaboration Practices to Effectively Implement Risk and Resilience (R&R) Approaches and Management.
	RPS A2. Developing a Capacity Building Plan to Identify Institutional and Individual Needs to Effectively Conduct Risk and Resiliency (R&R) Assessments at Transportation Agencies.
	RPS A3. Pilot Testing the Highway Risk and Resilience (R&R) Manual and Interface with Existing Asset Management Systems and Other Agency Functions
	RPS A4. Identifying Institutional Organizational and Procedural (IOP) Changes and Implementation Strategies for The Successful Adoption of the Highway R&R Manual.
Phase 3: R&R tools and revised R&R manual	**RPS A5.** Enhancing the Capacity Building and Implementation Plans to Incorporate Highway Risk and Resilience Manual and Tools
	RPS A6. Revising the Highway Risk and Resilience Manual
	RPS C1. Identifying and Developing Analytical Tools to Conduct **Risk** Assessments for Highway Assets.
	RPS C2. Identifying and Developing Analytical Tools to Conduct **Resilience** Assessments for Highway Assets.

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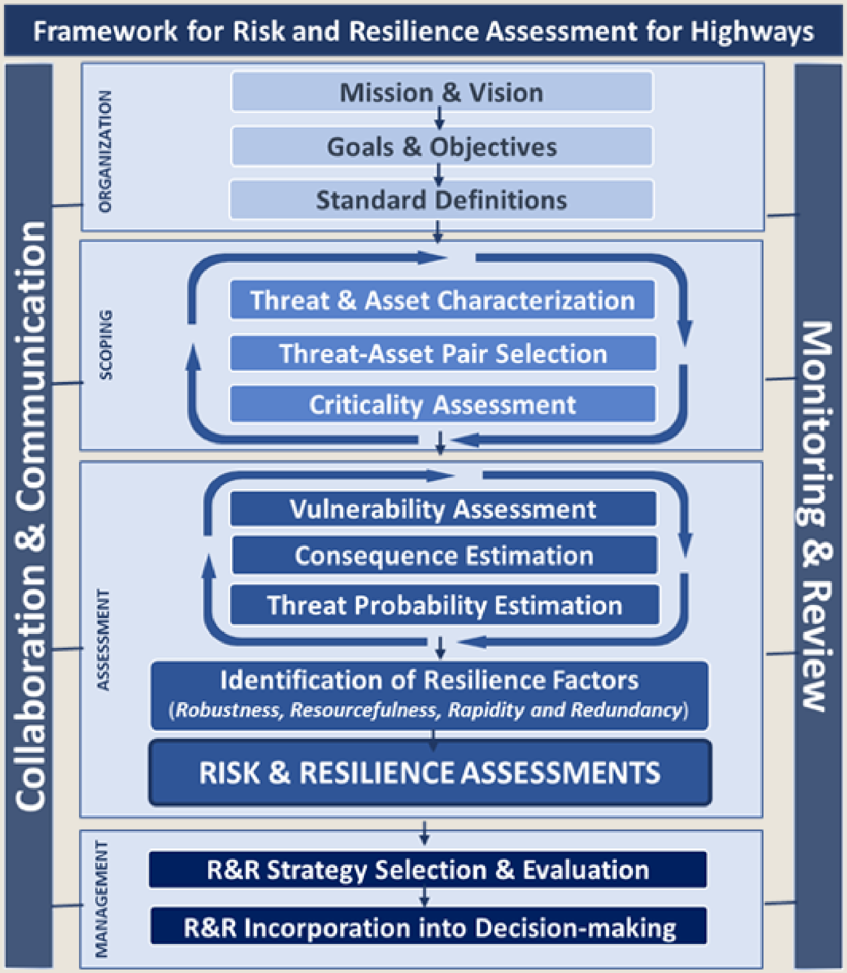
R&R Framework

- Followed the core bases for conducting quantitative R&R assessments
  - Threat probabilities by type of hazard and by geographic location;
  - Asset vulnerability to each applicable threat, appropriately considering asset resilience; and
  - Quantitative anticipated consequences from each applicable threat to each asset, appropriately considering the significant uncertainties in those consequences
- Flexible sequencing of steps
- Provides linkages to practice integration and decision-making



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R&R Framework

- Followed the core bases for conducting quantitative R&R assessments
  - Threat probabilities by type of hazard and by geographic location;
  - Asset vulnerability to each applicable threat, appropriately considering asset resilience; and
  - Quantitative anticipated consequences from each applicable threat to each asset, appropriately considering the significant uncertainties in those consequences
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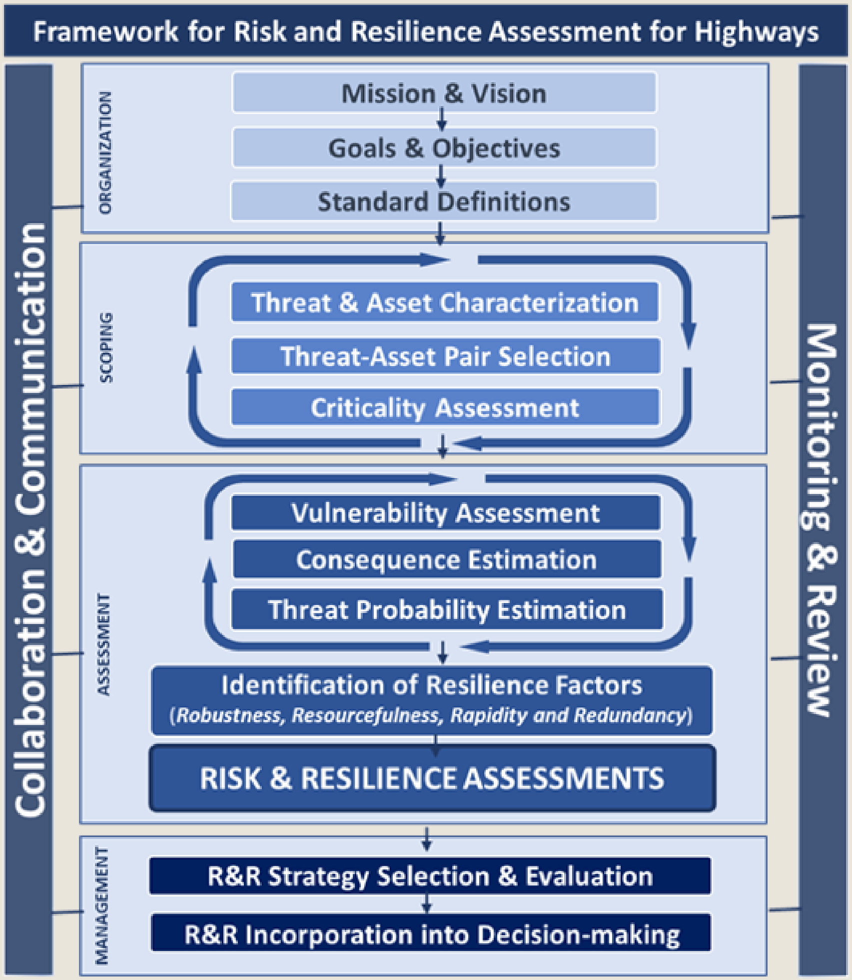

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Key Takeaways and Benefits to State DOTs

- Provides a research Roadmap to develop a comprehensive manual, tools, training, and implementation guidance for quantitative R&R assessment that satisfies the requirements of the new Infrastructure Investment and Jobs Act (IIJA)/BIL.
- Lays the framework for a consistent approach to R&R assessments, conduct economic analysis, project prioritization, and asst and performance management for the more efficient use of available funds.
- Advances the preparedness of the transportation sector for emerging threats, including extreme weather, climate change, and cyber.
- Enables state DOTs to communicate risk and make the business case for resilience investments in the face of uncertainty.

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Recommendations and Next Steps (1/2)

- Formal adoption of the Glossary of Terms and research Roadmap.
- Prioritization and implementation of prioritized projects in the Roadmap.
- Identify champions (within the AASHTO committee structure) and map out the sequence for necessary funding through NCHRP and/or other funding sources.
- Establish a working group or task force to oversee the execution of the proposed R&R roadmap and products (e.g., R&R Highway Framework/Manual).
- Enhance communication and collaboration among the transportation industry including TRB, AASHTO, state DOTs, and FHWA to ensure and streamline the successful development and implementation of the R&R framework/manual and associated products.

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Recommendations and Next Steps (2/2)

- Enhance continuous communication and collaboration among the principal investigators (PIs) of the different projects on the proposed research roadmap to ensure consistency and continuity of the projects.
- Ensure past and ongoing research in the area of risk and resilience is streamlined and incorporated into the development of the proposed roadmap products to reduce efforts, duplication, and improve consistency.
- It is important to recognize that due to the long-term timeframe of the roadmap, it should be an interactive process where communication with the different parties involved in the projects may need to respond to continuous feedback.
- While this research roadmap addresses highway assets explicitly, the research team recognizes that the R&R framework can be expanded to address a multi-modal system.