NCHRP 08-36, Task 146

Incorporating Resilience into Transportation Planning and Assessment

Requested by:

American Association of State Highway and Transportation Officials (AASHTO)
Standing Committee on Planning

Prepared by:

The RAND Corporation

June 2019

The information contained in this report was prepared as part of NCHRP Project 08-36, Task 146, National Cooperative Highway Research Program (NCHRP).

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Acknowledgements

This study was conducted for the American Association of State Highway Transportation Officials (AASHTO) Standing Committee on Planning, with funding provided through the National Cooperative Highway Research Program (NCHRP) Project 08-36, Research for the AASHTO Standing Committee on Planning. The NCHRP is supported by annual voluntary contributions from the state departments of transportation. Project 08-36 is intended to fund quick response studies on behalf of the Standing Committee on Planning. The report was prepared by the RAND Corporation. The work was guided by a technical working group that included:

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Disclaimer

Research Report

Incorporating Resilience into Transportation Planning and Assessment

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RAND CHEP

RR-3038-TRB
June 6, 2019
Prepared for Transportation Research Board, National Cooperative Highway Research Program

Preface

This report was initiated to inform the Transportation Research Board (TRB), a division of the National Research Council of the National Academies of Sciences, Engineering, and Medicine, about how to incorporate resilience into long range transportation planning for state departments of transportation and metropolitan planning organizations. This work considers not only the hazards associated with climate change but all hazards, while simultaneously considering stresses to transportation systems such as congestion that arise naturally but may be exacerbated by disturbances to the system. This work was sponsored by TRB under the National Cooperative Highway Research Program (NCHRP) project 08-36, Task 146.

We used a two-pronged approach to develop a conceptual framework for incorporating resilience, with both prongs being implemented in parallel. One prong consisted of interviews with stakeholders at state departments of transportation and planners in metropolitan planning organizations to better understand the role that transportation resilience plays in practice. We augmented these stakeholder interviews with reviews of the published literature on resilience generally, transportation resilience, and metrics associated with transportation and resilience. Based on the interviews and literature review, we developed a logic model to map the transportation system assets, first to transportation activities, then to transportation outputs and outcomes, and finally to socio-economic outcomes. This logic model, together with more traditional views of resilience, inform the development of the AREA (Absorptive capacity, Restorative capacity, Equitable access, and Adaptive capacity) interpretation of resilience for transportation. We then use the AREA interpretation to develop a suite of metrics that correspond to different aspects of resilience. Finally, we offer suggestions for how state departments of transportation and metropolitan planning organizations could modify the Federal Highway Administration's (FHWA's) Vulnerability Assessment Framework (VAF) to better incorporate resilience considerations and all hazards and stresses into long term decision making for transportation.

This report will be of interest to state and metropolitan transportation planners. The content is intended to be used to modify the long term transportation planning process to better incorporate resilience.

About the Community Health and Environmental Policy Program

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Abstract

This report provides an approach for incorporating resilience into transportation planning and assessment for state departments of transportation and metropolitan planning organizations. It builds off the existing Federal Highway Administration's Vulnerability Assessment Framework (VAF) to better incorporate principles of resilience into the decisionmaking process for long term transportation planning. Based on stakeholder interviews and reviews of the resilience, transportation resilience, and resilience metrics literatures, we develop a simple conceptual framework for adaptation of resilience principles to transportation. The AREA (Absorptive, Restorative, Equitable, Adaptive) interpretation of resilience contributes to this framework for incorporating resilience into decisionmaking and provides a starting point for development of a suite of metrics that can be used in planning and decisionmaking. By focusing on the criticality and exposure of various assets of the transportation network, the AREA interpretation provides a means to discover alternative options or strategies that should be considered when planning to increase the resilience of the entire transportation system through modifications and additions to those assets.

Our main recommendations for implementation of the Vulnerability Assessment Framework (VAF) to incorporate more resilience aspects are:

- Expand the objectives and scope to include shock and stresses not directly tied to climate change, including cyber attacks (See Table 3.1)
- Broaden the asset data to include human and equipment assets, using the logic model to guide expansions, and identify the criticality of these new assets (See Figure 3.4)
- Expand hazard data to consider a wider array of hazards and characterize whether the hazards is system wide or just influences a subset of assets (See Table 3.1)
- Use indicators identified in Chapter 4 to assess resilience of the system in a way that acknowledges the interaction of assets criticality and exposure.
- Engage stakeholders and decisionmakers when prioritizing options to help weigh tradeoffs that come with prioritizing options (See Chapter 2, Appendix A, and Appendix B)
- Utilize an established critique to facilitate the prioritization such as multi-criterion analysis, economic analyses, benefit-cost analysis, or life-cycle cost analysis. (See Chapter 2 and Appendix B)
- Consider the benefits of investment both in time of normalcy and times of disruption (See Figure 3.3)

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Acknowledgments

We thank Larry Goldstein of the Transportation Research Board for his overall support of the project. We also wish to thank our advisory board members, consisting of Elizabeth Robbins of the Washington State Department of Transportation, Elizabeth Alden of the Hillsborough, Florida Metropolitan Planning Organization, Stuart Anderson of Iowa Department of Transportation, Don Arkle of Alabama Department of Transportation, William Eastin of the Georgia Department of Transportation, Jeffrey Harris of the Utah Department of Transportation, Keith Killough of the Arizona Department of Transportation, James Ritzman of Pennsylvania Department of Transportation, Catherine Ross of Georgia Technical Institute of Technology, Bradley Sharlow of Michigan Department of Transportation, Lynn Weiskopf of New York Department of Transportation, Harlan Miller of the Federal Highway Administration (FHWA), and Matthew Hardy of the American Association of State Highway and Transportation Officials (AASHTO), who provided excellent guidance over the course of the project, including formal comments.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AREA	Absorptive, Restorative, Equitable, Adaptive
BRIC	Building Resilient Infrastructure and Communities
DOT	Department of Transportation
FAST	Fixing America's Surface Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
LRTP	Long Range Transportation Plan
MAP-21	Moving Ahead for Progress in the 21st Century
MATA	Memphis Area Transit Authority
MOR	Measure of Resilience
MPO	Metropolitan Planning Organization
PPD-21	Presidential Policy Directive 21
RI	Resilience Investment
RISE	Resilience Innovations Summit and Exchange
RPC	Regional Planning Commission
SoVI	Social Vulnerability Index
TIP	Transportation Improvement Program
TOSE	Technical, Organizational, Social, Economic
TRB	Transportation Research Board
VAF	FHWA Vulnerability Assessment and Adaptation Framework
VMT	Vehicle Miles Travelled

1. Introduction

The Federal Highway Administration's (FHWA's) Vulnerability Assessment and Adaptation Framework is "a manual to help transportation agencies and their partners assess the vulnerability of transportation infrastructure and systems to extreme weather and climate effects." While this document helps transportation planning agencies incorporate climate adaptation into their existing processes, it lacks a broader framework for incorporating resilience into the transportation planning process. For this reason, the Transportation Research Board of the National Academies of Science, Engineering, and Medicine, which serves to advise the nation on issues of transportation, contracted with a team of RAND researchers to develop an evidence-based framework to incorporate resilience into the implementation of the FHWA Vulnerability Assessment and Adaptation Framework (VAF), and into transportation planning for state departments of transportation (DOT) and metropolitan planning organizations (MPO).

The VAF provides a six-step process to frame planning around mitigating and adapting to vulnerabilities in a transportation system. These six steps are:

1. Articulating objectives and defining study scope
2. Obtaining asset data
3. Obtaining climate data
4. Assessing vulnerability
5. Identifying, analyzing, and prioritizing adaptation options
6. Incorporating assessment results into decision making

The focus of the VAF is on mitigating and adapting to vulnerabilities that arise due to climate change. More broadly though, the same framework can be used to plan and assess resilience of the transportation system to not only vulnerabilities arising from climate change but also shocks and stressors arising from other sources. Rather than to develop a new resilience centered planning and assessment framework, we offer an implementation strategy focus on resilience that uses the VAF as a backdrop for implementation. Since organizations may have previous experience using the VAF, our approach simply changes the lens by which the framework is view to more broadly incorporate resilience to a broader suite of vulnerabilities. Our implementation strategy is to view the system of assets within a network through the AREA lens to allow for a broader suite of strategies to increase the system resilience taking into account the criticality and exposure of different network assets in the system.

One of the challenges in developing a coherent definition and conceptual framework for the transportation sector is that the transportation sector is but one system in the system-of-systems that makes up the larger socio-economic system. Additionally, transportation is a means to an end and not an end in itself. People use the transportation system to access economically,

socially, and environmentally valuable locations. Overlaying these ideas on a more traditional characterization of resilience may cause some contradictions or miss key aspects of the value of the transportation system in times of stress or shock. Therefore, our approach to a conceptual framework for better integrating the ideas of resilience into the transportation system is to recast the objectives of resilience in terms of transportation related concepts. This recasting will allow transportation planners to more easily incorporate the ideas of resilience into long term system wide planning and the decisionmaking process.

Our main recommendations for implementation of the VAF to incorporate more resilience aspects are:

- Expand the objectives and scope to include shock and stresses not directly tied to climate change, including cyber attacks (See Table 3.1)
- Broaden the asset data to include human and equipment assets, using the logic model to guide expansions, and identify the criticality of these new assets (See Figure 3.4)
- Expand hazard data to consider a wider array of hazards, including cyber attacks, and characterize whether the hazards is system wide or just influences a subset of assets (See Table 3.1)
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- Engage stakeholders and decisionmakers when prioritizing options to help weigh tradeoffs that come with prioritizing options (See Chapter 2, Appendix A, and Appendix B)
- Utilize an established critique to facilitate the prioritization such as multi-criterion analysis, economic analyses, benefit-cost analysis, or life-cycle cost analysis. (See Chapter 2 and Appendix B)
- Consider the benefits of investment both in time of normalcy and times of disruption (See Figure 3.3)

We used a two-pronged approach to develop a conceptual framework for incorporating resilience, with both prongs being implemented in parallel. One prong consisted of interviews with stakeholders from Metropolitan Planning Organizations (MPO) and state departments of transportation (DOT) to assess the state of the practice with respect to resilience in transportation and to understand how stakeholders use information on the costs and benefits of resilience when making long-term investments in highway and transportation infrastructure. The other prong included: reviews of the broad literature on resilience with a special attention to system-of-systems frameworks; the literature on defining and incorporating resilience into transportation planning; and metrics for transportation resilience. In addition, a study team member attended Transportation Resilience Innovations Summit and Exchange (RISE) in Denver, CO in 2018. The goal of attendance was to understand the current dialogue around transportation resilience among key stakeholders which included state level DOTs, several MPOs, private transportation consulting organizations, and academics among others in transportation with a focus on resilience. These pieces inform our conceptual framework and provide a framing of resilience

that can be used to modify the implementation of the VAF. Our conceptual framework acknowledges the broad network of organizations involved in transportation planning, and the role of the transportation system as one element of a broader system-of-systems that aims to provide value to users. The transportation network we refer to includes approximately 4,200 people who work for MPOs across the 50 states (Kramer *et al*., 2017), as well as the 50 state DOTs. Embedding the framework within this broader system-of-systems perspective helps planners discover alternative options or strategies that should be considered when planning to increase the resilience of the transportation system.

At present, there is no single theory that provides a definitive definition of resilience, nor is there a widely agreed upon practice for achieving resilience. From some perspectives, resilience is not a measurable outcome at all, but is rather a way of approaching all aspects of system over the course of the lifecycle of the project, from planning to operation and maintenance. From a federal perspective, Presidential Policy Directive 21 (PPD-21) provides a foundation for a definition of resilience for critical infrastructure. It defines resilience as:

> "… the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience include the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."[1]

The Fixing America's Surface Transportation Act (FAST Act), signed into law in December 2015, requires the planning process to consider resilience, generally, and stormwater, specifically. Although the FAST Act requires resilience to be considered, it does not provide guidance for how to incorporate resilience into the planning process. Further, different communities face different shocks and stresses on their transportation infrastructure. Thus, the aim of this report is to provide some guidance to transportation planners for how resilience may be incorporated into the assessment and planning for transportation infrastructure.

Based on our reviews of the literature and interactions with transportation stakeholders, we have developed a logic model for mapping the transportation system assets to activities, outputs, and outcomes, and finally to community well-being. By initially mapping the system, we are better able to capture how modifying the system translates into outcomes that planning organizations aim to improve. We then combine this system mapping with a multidisciplinary view of resilience to develop a conceptual framing of resilience for that transportation system that we call the AREA (Absorptive capacity, Restorative capacity, Equitable access, and Adaptive capacity) approach to resilience. Each of these aspects of resilience suggests a means through which to increase the resilience of the system, although by different methods.

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[1] https://www.dhs.gov/sites/default/files/publications/PPD-21-Critical-Infrastructure-and-Resilience-508.pdfhttps://www.dhs.gov/sites/default/files/publications/PPD-21-Critical-Infrastructure-and-Resilience-508.pdf Office of the Press Secretary, "PRESIDENTIAL POLICY DIRECTIVE/PPD-21 Critical Infrastructure Security and Resilience ", Washington, DC: White House, February 12, 2013. https://www.dhs.gov/sites/default/files/publications/PPD-21-Critical-Infrastructure-and-Resilience-508.pdf

Importantly, the network nature of the transportation system means that the aim of investments in resilience is to reduce reliance on individual assets or to reduce the assets' exposure in different locations so that no one cascading effects across the network are reduced. That is, resilience investments should improve the operation of the network during normal as well as disrupted times, while avoiding cascading failures of the network when disruptions do occur.

In the next chapter, we provide an overview of how resilience has been considered in transportation specifically drawing on our two pronged approach that appears in Appendices A and B. Chapter 3 develops our logic model and conceptual framework. Chapter 4 provides a summary of metrics that could be used for measuring resilience based on the AREA approach to resilience. Chapter 5 incorporates the conceptual framework into the implementation of the existing VAF. Chapter 6 provides some general conclusions for planners about incorporating resilience into the transportation system.

2. Resilience in a Transportation Context

This chapter summarizes the results of our two-pronged approach for reviewing how resilience has been considered in transportation. First, we describe our discussions with transportation experts, then, second, we conduct a broad literature review of resilience generally and how resilience has been specifically applied to transportation. Appendix A provides more details on our stakeholder interactions and Appendix B provides additional information about the literature's treatment of resilience generally. Building on these interviews and the broad frameworks of resilience, we then focus on how resilience is used and applied in a transportation context. We begin by discussing how the transportation community defines resilience, measures resilience, and incorporates resilience into transportation decisionmaking. Next, we discuss how transportation planners consider equity and non-transportation benefits. Finally, we examine who benefits from transportation infrastructure.

Stakeholder Interviews

The stakeholders that we spoke with included organizations directly involved with transportation infrastructure planning and investments through implementation, planning, or policy including MPOs, state DOTs and federal transportation offices and committees. A total of nine interviews were conducted with eight organizations including four metropolitan planning organizations located in Florida, Louisiana, Tennessee and Texas, two state level departments of transportation; Colorado & Iowa, and two federal level organizations based in Washington D.C. We intentionally reached out to organizations from various regions of the U.S. to hear from organizations facing different geographies and contexts, although some organizations did not respond or declined participation. Stakeholders that were interviewed provided valuable insight about how transportation planners and policymakers consider resilience, and what is needed in the future to ensure a more resilient transportation system.

The interviews included discussion of which other organizations stakeholders interact with for transportation planning, both within the transportation system as well as outside of it. This was important to capture because it relates to not only transportation system outcomes but also the broader socio-economic outcomes. Other topics discussed included the stakeholder's priorities; the benefits, costs, and challenges they consider; how they use available information to inform long-range planning and investments in highway and transportation infrastructure; and their perspective on what is needed for the system to become resilient or maintain resilience as well as how transportation resilience is defined and measured. A detailed description of the discussions can be found in Appendix A. In this chapter, we discuss the main topics related to

the conceptual framing, metric discussion and further recommendations considered in later chapters.

The priorities noted by stakeholders relate to maintaining current infrastructure, facilitating quick restoration of infrastructure following disruptions, and updating and adding services such as public transportation to improve outcomes such as congestion, safety, environmental impact, and job access. Those interviewed highlighted that transportation infrastructure and services contributes to benefits beyond the transportation system – transportation impacts other social, economic, and environmental systems. Stakeholders noted that they work with many types of organizations and professions, including businesses, medical districts, hospitals, public health departments' divisions for water and air quality, and commissions that reach out to special interest constituent groups. Those interviewed also noted they work across different levels of government, including not only the counties and jurisdictional governments where the interviewee is located, but also with neighboring jurisdictions.

Those interviewed also noted challenges that can limit the ability of the transportation system to provide benefits, which highlight the disruptions to which transportation systems should be resilient. The challenges include disruptions and risks related to extreme weather events (i.e. flooding, high level winds, storm surge), other environmental physical threats such as rockfall, land loss and erosion, infrastructure outages, and other human induced threats such as cybersecurity threats or even population growth as a threat in terms of increased demands and needs on the infrastructure. Related to planning and implementation challenges include limited funding, limited data for planning, lack of agreement on priorities for different levels of government, management turnover, slow adoption of new practices, lack of all hazards planning and underdeveloped public infrastructure. Stakeholders expect new challenges to arise in the future, such as autonomous vehicle adaptation, coordination between organizations for long-term planning with a resilience focus, increased wear and tear on infrastructure, climate change impacts, and sustainable funding.

As we discuss further in the below section, "How does the Transportation Community Define Resilience?" there is not a single precise definition of resilience across all transportation agencies. Some of the organizations we interviewed had established their own definition of resilience, and all interviewees were familiar with the term. We summarize their collective understanding of resilience as follows: transportation resilience is the ability to adapt, recover, and respond to—and bounce back quickly from— threats to physical infrastructure and operations, threats to cybersecurity, terrorism, and all hazards; and the ability to minimize impact and ensure the transportation system is still usable following a shock or stressor. The factors that interviewees mentioned would contribute to resilience include a culture shift that promotes a national understand of transportation resilience and efforts to achieve it; cross-sector coordination for transportation, planning, short, medium and long-term strategies; clear policies and requirements to make implementation, planning, and reporting understood and implemented similarly for all transportation organizations; and improved understanding of the connectivity

between transportation systems and critical assets. Other factors included data sharing, resilience targeted funding, infrastructure redundancy and alternatives in an event, and knowledge of impact of events including on critical assets and other systems such as the economy.

Finally, while those interviewed do not currently have many quantitative metrics for measuring transportation system resilience and its impacts on socio-economic and environmental systems, they do collect and monitor data now. Examples of current metrics stakeholders can access include the use of crash data, community participation in transportation, asset inventory, infrastructure damage and cost and repair data, road closure time, delay time, and congestion rates. Metrics and data interviewees noted they would like to have related to resilience included avoided disruptions, lives saved and other quantifications of safety impacts, how air quality changes with travel fluctuations, flood risk by asset, frequency of required maintenance, and the economic cost of transportation disruption.

What is Resilience?

The literature suggests three main themes associated with the concept of resilience: (1) reducing the likelihood of a disaster and the ability of a community to absorb or resist a shock; (2) increasing the adaptability of a system while still maintaining function in the presence of a shock; and (3) reducing the time to recovery to normal functioning that may be different than pre-event functioning. These themes translate into capacities at the community or regional level that are essential to achieving resilience: (1) absorptive or resistive capacity; (2) adaptive capacity; and (3) restorative capacity (Norris *et al*, 2008). In addition, there has been a movement to incorporate equity or equitable access into resilience (Nicholls, 2001).

Generally, conceptual frameworks can be categorized into two groups: (1) systems that segment the world by public service sectors (e.g. electric, water, transportation); and (2) systems that segment along functional lines (e.g. social, built, natural). This segmentation can miss important interdependencies between systems. A community with resilient subsystems is not necessarily resilient as a whole because of interdependencies among the subsystems. Indicator and metric systems tend to isolate the different subsystems in the conceptual frameworks rather than focusing on the interdependencies. Decisionmaking around resilience forces communities to make tradeoffs across many outcomes and alternative frameworks help to better conceptualize those tradeoffs. Importantly, system-of-systems approaches are the frameworks that have been used and can be directly applied to transportation either in isolation or in thinking about the socio-economic system that the transportation system is embedded within. A more detailed discussion of resilience and conceptual frameworks for incorporating resilience can be found in Appendix B.

How does the Transportation Community Define Resilience?

The precise definition of resilience varies across transportation entities, but reflects the ability to adapt, recover, and respond to a variety of threats to physical infrastructure, operations, cybersecurity, terrorism, and all hazards, although the literature is largely focused on resilience to natural disasters. 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 State DOTs and MPOs have similar definitions of resilience and is consistent with our stakeholder interactions. Some definitions appear as informal statements in meeting minutes, while others are explicitly defined in transportation planning documents. Examples of definitions of resilience include "reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs," (Minnesota DOT, 2017), the ability of the transportation system "to quickly respond to unexpected conditions and return to its usual operational state," (Wisconsin DOT, 2009), and "the ability of the transportation system to withstand and recover from incidents." (Tennessee DOT, 2005). As noted by Dix et al., (2018), DOTs and MPOs mainly differ on how they propose to improve their resilience capabilities; "Some emphasize the importance of system adaptive capacity and robustness, while others prioritize swiftness in the recovery response." Many agencies include both adaptation and recovery concepts within their treatments of resilience.

However, there are some issues on which state DOTs and FHWA have not always agreed, such as the value of fatality prevention in the calculation of risk (Hanley, 2004). Another source of variation in the meaning of resilience is the type of disruption the transportation network is intended to avoid or quickly mitigate. Resilience is most commonly referred to in the context of natural hazards. However, some DOTs and MPOs focus on resilience to any type of disruption to the movement of goods or people, such as traffic jams. In some cases, the focus of resilience might be on avoiding or mitigating the impacts of fiscal uncertainty, such as rising fuel prices, or even crime.[2]

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[2] "The Madison Area Transportation Planning Board (Madison, WI) has goals to "develop a transportation system that is resilient in the face of climate change and rising fuel prices in the future" and to "reduce vulnerability of the public and the region's transportation infrastructure to crime and natural hazards."" (Dix et al,, Brenda, Beth Zgoda, Amanda Vargo, Samatha Heitsch, and Taylor Gestwick, *Integrating Resilience into the Transportation Planning Process: White Paper on Literature Review Findings*, U.S. Department of Transportation, Federal Highway Administration, FHWA-HEP-18-050, May 2018). . https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/planning/integrating_resilience.cfm . Also see Madison Area Transportation Planning Board. April 2017. ", Regional Transportation Plan 2050." Available at: http://www.madisonareampo.org/planning/documents/RTP_2050_Report_Final.pdf. , April 5, 2017. http://www.madisonareampo.org/planning/documents/RTP_2050_Report_Final.pdf

How does the Transportation Community Measure Resilience?

Given the lack of consensus on the definition of resilience within and outside of the transportation sector, it is unsurprising that no widely-accepted metric exists for measuring transportation resilience. While many transportation entities have working definitions of resilience, few have quantitative metrics to measure resilience. Ninety-two percent of states surveyed by Flannery, Pena, and Manns (2018) reported having no specific resilience metrics in place for transportation. A wide variety of possible metrics have been suggested and tested. For example, Parkany and Ogunye (2016) suggest a series of potential metrics, aligned with Bruneau's four components of resilience (Table 2.1). Chapter 4 further discusses a wide variety of metrics used to measure different aspects of resilience.

Table 2.1 Resilience Metrics Based on Bruneau's Components of Resilience

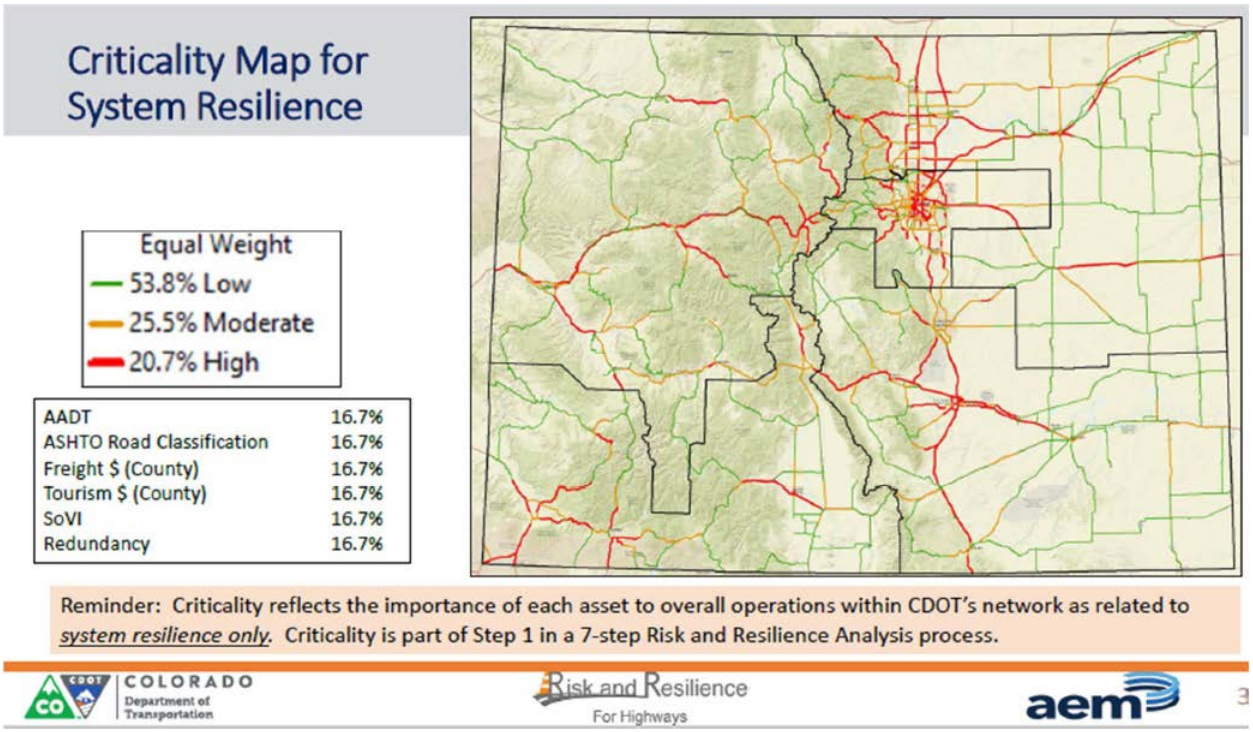
Component	Metric
Robustness	Hours of congestion
	Spatial extent of congestion
	Travel time index
	Optimal spare capacity
	Pavement condition
	Weather impacts that can be absorbed without disruption
	Volume of congestion
Redundancy	Distance to alternative routes
	Percentage of corridor with alternate routes
	Available capacity on alternative routes
	Congestion on alternative routes
Redundancy (cont.)	Availability of alternative routes, such as graph theory connectivity score
	Transit alternatives
	Adjacent park and ride lots
Resourcefulness	Safety service patrol
	Average incident duration
	Funding Availability
	Variable message signs
	Weather stations
	The use of alternative routes
	Construction projects
	Weather mitigation capability
Rapidity	Time until re-opened or fully restored for top 5% incident
	Average construction project duration

Source: Authors' Interpretation

A common desire is to combine measures of different aspects of resilience into a single representative number. Such one-dimensional measures may be enticing because they offer policy makers a simple way to prioritize across different aspects of resilience, but these indices can lack the ability to communicate important nuances. This direct comparison between different aspects of resilience is possible because decisions about trade-offs between different aspects of resilience are implicitly made within the modeling process when combining different measures of resilience into a single measure. One example in the transportation literature comes from research sponsored by the Colorado Department of Transportation and FHWA (Jensen & Kemp, 2017). The study provides a methodology to support investment decisions in Colorado's I-70 corridor. The first step in its resilience evaluation process is to assess asset criticality. Criticality for different roadway segments is calculated as the evenly weighted combination scores based on six different rankings: annual average daily traffic (AADT), the Association of American State Highway and Transportation Officials (AASHTO) Roadway Classification, Freight value per ton at the county level in millions of dollars per year; Tourism dollars generated at the county level in millions of dollars per year; Social Vulnerability Index (SoVI) at the county level (Cutter, Boruff et al. 2003); and system redundancy as measured by CDOT's Redundancy Map. The weighted sum of these values for any given roadway segment produces the criticality score for that segment.

As shown in Figure 2.1, roadways with the lowest 53.8 percent of scores were deemed "Low Criticality," the next 25.5 percent were deemed "Moderate Criticality," and the 20.7 percent with the highest scores were deemed "High Criticality." Taking the inputs and weights as given, the ranking provides a justification for where to focus resilience efforts within the evaluated system. Planners using this process would prioritize investments in "High Criticality" segments over investments in "Low Criticality" segments.

Figure 2.1. CDOT Asset Criticality Map



Source: Jensen & Kemp (2017)

These criticality scores are not a resilience metric, and Figure 2.1 is not a map of system resilience – it is a prioritization of roadway segments based on an aggregation of discrete qualities of the roadway segments. Preferences between these different qualities of the roadway segments are determined by the preferences incorporated into the model.

Planners care about how "critical" a roadway segment is in terms of usage, availability of alternatives, equity impacts, and a host of other factors related to the services the route provides. But when making investments to improve the resilience of a roadway segment to various risks, planners also care about the amount and types of risk to which the segment is exposed. The I-70 corridor study next examines the anticipated annual "risk," or expected loss, for each potential hazard, which is calculated as:

$$\text{Risk} = C \times V \times T$$

Where C is the total monetary losses that might occur if the event happens, V is the probability that the amount C will be lost if the hazard occurs, and T is the probability the hazard will occur in a given year. The report then examines various mitigation options and calculates the change in expected losses divided by the cost of the intervention, essentially performing a form of cost benefit analysis.

Many states have programs for identifying and measuring risk, but few have identified funding sources for addressing identified risks. Making a business case for increasing resiliency can be difficult because it involves reducing the risk of costs that have not yet occurred, as opposed to reducing costs that are currently observed and well-measured. For this reason, identifying and using proper metrics to measure resilience is critically important.

How is Resilience Being Incorporated into Transportation Decisionmaking?

A properly functioning network of transportation infrastructure enables and empowers the movement of people and goods within and between communities. Disruptions in this network reduce economic productivity, harming local commercial activities and local tax revenues. These disruptions also directly harm individuals' well-being by restricting individuals' mobility or creating safety hazards. To avoid these costs, State DOTs and local MPOs make investments in the transportation network that avoid or quickly mitigate these impacts. Such investments are broadly described as investments in resilience.

Most State DOTs explicitly consider resilience as a goal or objective. In addition to pursuing resilience for the purpose of achieving various benefits, "State DOTs and MPOs largely referenced federal law and regulations as a reason for including resilience in their transportation planning" (Dix et al, 2018). Relevant laws include the 2015 Fixing America's Surface Transportation (FAST) Act,[3] the 2012 Moving Ahead for Progress in the 21st Century (MAP-21) Act,[4] and the Department of Homeland Security National Infrastructure Protection Plan.[5] The FAST Act adds resilience to sections of the United States Code (Particularly Title 23—Highways and Title 49—Transportation). For example, 49 CFR § 5303 (a)(1), in discussion metropolitan transportation planning, now seeks to "encourage and promote the safe and efficient management, operation, and development of resilient surface transportation systems." Similar phrasing is introduced in other sections of 23 CFR and 49 CFR. Some state laws also

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[3] Available at: https://www.fhwa.dot.gov/fastact/legislation.cfm. U.S. Department of Transportation, Federal Highway Administration, "Fixing America's Surface Transportation Act or "FAST Act"," May 5, 2015. As of February 26, 2019. Sections 1201 and 1202 require that planning agencies incorporate resilience into the planning process.

https://www.fhwa.dot.gov/fastact/legislation.cfm

[4] Available at: https://www.fhwa.dot.gov/map21/legislation.cfm. U.S. Department of Transportation, Federal Highway Administration, "Fixing America's Surface Transportation Act or "FAST Act"," May 5, 2015. As of February 26, 2019. MAP-21 Section 1115 focuses on improving freight transportation resilience.

https://www.fhwa.dot.gov/fastact/legislation.cfm

[5] Available at: https://www.dhs.gov/national-infrastructure-protection-plan. U.S. Department of Homeland Security, "National Infrastructure Plan." As of February 28, 2019:

https://www.dhs.gov/national-infrastructure-protection-plan.

encourage or require the incorporation of resilience into transportation planning, such as California's Executive Order B-30-15.[6]

In practice, resilience investments involve either identifying and measuring risk, or protecting existing transportation system elements from identified risks. These risks are typically environmental risks, although other risks such as cybersecurity or public health are sometimes considered. FHWA is partnering on eleven projects that aim to enact resilience through either (1) Integrating resilience and durability into agency practices, (2) Using available tools and resources to assess the vulnerability and risk of transportation projects or systems, and/or (3) Deploying a resilience solution and monitoring performance.[7] Most of these projects involve hardening transportation infrastructure against damages caused by environmental stressors such as extreme weather events, climate change, or erosion. One exception, a project by the Utah Department of Transportation, focuses instead on measuring and communicating risk information in the form of GIS maps.

Other approaches to increasing resilience could involve moving transportation system elements away from high-risk areas or supporting alternate routes that are not exposed to the same risks. Examples of such resiliency efforts in transportation are rare. The Code of Federal Regulations Title 23, Vol. 1, Part 667, titled "Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events," requires state DOTs to "conduct statewide evaluations to determine if there are reasonable alternatives to roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events" (23 C.F.R. § 667.1). Reasonable alternatives could include any effort (such as moving a facility or implementing design changes) that reduces the need for federal funds, better protects public safety and health, and meets relevant transportation needs. The baseline statewide evaluation was due no later than November of 2018. In addition, state DOTs must update this overall evaluation at least every four years; and they must provide any needed updates to planned or required improvements to roads, highways, or bridges after they are affected by an event (23 C.F.R. § 667.7).[8] Alternative routes are not always prepared to absorb the demand that occurs when a major transportation route is closed. The Colorado DOT, for example, has been very proactive in thinking about system resilience rather than focusing solely on hardening infrastructure. States are also required to develop a risk-based asset management plan for the National Highway System per 23 U.S.C. 119(e)(1), MAP-21 § 1106 (USDOT, 2017).

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[6] Available at: https://www.ca.gov/archive/gov39/2015/04/29/news18938/ Exec. Order No. B-30-15 (2015).

[7] Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/extweatherpilot.cfm. U.S. Department of Transportation, Federal Highway Administration, "2018 - 2020/2024 Pilot Program: Resilience and Durability to Extreme Weather," December 10, 2018. As of February 28, 2019:

https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/extweatherpilot.cfm.

[8] See Code of Federal Regulations, Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events. 23 C.F.R. § 667 (2016) https://www.law.cornell.edu/cfr/text/23/part-667

Dix et al. (2018) identify "points at which resilience can tie into transportation planning processes," noting that, "although State DOTs have goals related to resilience, most goals either do not have specific performance measures, or they map to performance measures" that are not directly related to resilience to natural hazards. Where performance measures exist, they are often related to flood risk exposure or stormwater management capabilities. Dix et al. note that "many MPOs have also begun identifying resilience strategies" but have often not yet performed formal vulnerability analyses or established evaluation criteria. In part, this finding may reflect uncertainty in identifying specific evaluation criteria for resilience beyond flood risk exposure.

Resilience policies, regulations, and laws affect how money can be spent on resilience efforts. For example, under the Stafford Act, buildings, shelters, utilities, and land that receive disaster relief must become insured to receive federal funding in the future (Stafford Act § 311(b) & § 602(a)(6)). In some cases, this requirement is waived at the state level when there is limited availability of insurance or when the cost of insurance is high (Tonn, Czajkowski, and Kunreuther, 2018). The Stafford Act previously limited disaster assistance funding to only restoring facilities to their original condition. The Disaster Recovery Reform Act of 2018 changed this rule, allowing applicants to update facilities to meet the latest codes and standards. The President may also set aside a portion of the Disaster Relief Fund to go towards hazard mitigation, the Building Resilient Infrastructure and Communities (BRIC) program (Abbott et al., 2018, Stafford Act § 1234).

How do Transportation Planners Consider Equity?

Many experts point out that transportation planning has shifted from away from a focus on mobility – the ease with which one can move around the transportation system. Instead, some authors call for a focus on equity – the ability of the system to provide the opportunity for access to all members of the community. Greg, Levine, and Shen (2013) argue that the focus on mobility, using metrics such as travel speed and congestion, was misplaced because these metrics examine the transportation system itself rather than the core outcomes of system users. They argue for a shift in focus to "access," the ability of users to interact with a large number of people and places in a fixed amount of time. In particular, they highlight metrics focused on job access, such as the cumulative opportunity and gravity metrics (discussed in Chapter 4). Jobs are not the only destination users might want to access. Nicholls (2001) looks at access to public parks as an example of access to leisure activities.

Manaugh, Badami, and El-Geneidy (2015) also highlight the shift away from mobility-based transportation planning. They look at the long-range transportation plans and related documents from 18 large cities in Canada and the U.S. From their perspective, transportation planning is shifting from mobility-based thinking to sustainability-based thinking, where sustainability is built on the "3Es" framework (Environment, Economics, and Equity), a shift that they point out

is difficult. One reason for the difficulty is that equity outcomes are often more intangible or abstract than mobility outcomes, making it more difficult to measure progress.

Litman (2014) defines multiple types of equity that are pursued in transportation planning. Horizontal equity is concerned with distributional differences between individuals and groups with equal abilities and needs. One example is considerations of whether similar neighborhoods have similar access to public transit. Obtaining horizontal equity involves ensuring similar groups "receive equal shares of resources, bear equal costs, and in other ways be treated the same." This version of equity corresponds to the colloquial usage of "fairness." Vertical equity is concerned with distributional differences between groups that differ in ability or need. One example is considerations of whether groups with restricted mobility have appropriate access to transportation services; the average distance residents of a senior living community can walk to reach a bus stop might be different than the average distance students at the community college can walk to reach a bus stop. Litman suggests ability or need might vary across individuals or groups with different income, social class, mobility need, or ability. Transportation policies may be regressive or progressive depending on whether they favor certain groups over others. Importantly, Litman points out that these different concepts of equity can sometimes have competing goals: "Horizontal equity requires that users bear the costs of their transport facilities and services, but vertical equity often requires subsidies for disadvantaged people. Therefore, transport planning often involves making tradeoffs between different equity objectives."

How do Transportation Planners Consider Non-Transportation Benefits?

The planning documents of most DOTs and MPOs suggest the main purpose of resilience investments is to facility the safe and efficient movement of people and goods. However, MPOs often cite additional goals, such as environmental objectives or supporting emergency management capabilities. Indeed, 49 CFR § 5303 (a)(1), mentioned above, states that resilient surface transportation systems should be encouraged "while minimizing transportation-related fuel consumption and air pollution through metropolitan and statewide transportation planning processes." Again, similar phrasing is used in other sections of the U.S. code. And again, state laws and policies such as the Massachusetts Global Warming Solutions Act, the Massachusetts DOT GreenDOT policy, and the Massachusetts Clean Energy and Climate Plan for 2020 can encourage the incorporation of non-transportation benefits, such as greenhouse gas emission reductions, into transportation planning.

In the 2035 Maryland Transportation Plan, the Maryland DOT includes a goal to "improve the State's emergency management capabilities for natural and man-made disasters by completing emergency management plans and training (MDOT, 2016)."

Several local transportation planning authorities are also responsible for environmental activities, and hence have goals that pair transportation planning with environmental stewardship. For example, the Shasta (CA) Regional Transportation Agency's "2015 Regional

Transportation Plan for Shasta County" includes the goal to "Practice and promote environmental and natural resource stewardship." The Chittenden (VT) County Regional Planning Commission's Climate Action Guide's first priority strategy is to "reduce greenhouse gas emissions from transportation/land use," by investing in emission-reducing transportation options such as Park and Ride facilities, infrastructure for electric vehicle charging, and funding facilities that support bicycles and pedestrians. The plan also calls for implementing demand management programs and increasing the availability of public transit (CCRPC, 2014). Similarly, the Northeast Ohio Areawide Coordinating Agency, which provides transportation and environmental planning for the greater Cleveland area, issued their "AIM Forward 2040" plan that includes the goal "Enhance the natural environment and ecology of the region by improving air, land and water quality, conserving transportation energy, addressing climate change, and by identifying and preserving existing critical natural resources and environmentally sensitive areas." Hawaii's DOT has a goal to ""promote long-term resiliency, relative to hazard mitigation, namely global climate change, with considerations to reducing contributions to climate change from transportation facilities, and reducing the future impacts of climate change on the transportation system." (CH2MHILL, 2014)

Beyond greenhouse gas emissions, other hazards that are unique to particular regions, such as permafrost melt, coastal erosion, and volcanic activity, can impact both transportation planning and a wider variety of environmental benefits (duVair, P., Wickizer, D., and Burer, M. J., 2003).

Who Benefits from Transportation Infrastructure?

While a variety of frameworks for measuring and assessing transportation resilience are available, there is not yet a large body of literature that empirically links improvements in those metrics to increased benefits for users. Regardless, there is a broad perception based on models and estimates that these projects can help avoid significant economic losses, while also addressing equity considerations. For example, there is a shared understanding in transportation planning that infrastructure down time impacts businesses. Post disaster, 40 percent to 60 percent of small businesses do not re-open (FEMA, undated). Our understanding of how the transportation system supports economic well-being suggests that a more resilient transportation system would help reduce business closures due to disasters. Therefore, transportation investments focus on benefits related to economic losses for businesses within a community that were avoided due to averted transportation disruptions, improved safety through mode choice changes for individuals leading to reduced accidents and injury while using the infrastructure, and reduced operational and maintenance costs for the transportation system (APTA, 2016; Burkhardt et al, 2003). Other benefits less commonly discussed in the transportation system literature include benefits due to targeted investments, such as community improved health when users increase physical activity through biking or walking to destinations (Wu et al, 2019). Other

health benefits include improved air quality through reduced traffic-related green-house gas emissions (Park and Sener, 2019).

Summary

Overall, the transportation literature appears broadly consistent with FHWA Order 5520 definition of resilience as “the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.” Much of the written literature focuses on disruptions caused by natural disasters, although there are some sources that reflect a broader set of disruption concerns. There is agreement on the broad intention of resilience, but uncertainty about how to best incorporate resilience into the planning process. This is in part a measurement challenge. In some cases, their planners are uncertain about how to measure resilience. In other cases, planners have access to resilience metrics but are unsure how to convert metrics into specific and quantifiable policy objectives. In part, this search for how to implement resilience reflects an ongoing change in mindset from one focused on providing citizen with mobility options to a mindset focused on providing citizens with access to a system, even when that system faces shocks or stresses.

3. Conceptual Framework

In this and the following two chapters, we discuss our conceptual framework, which expands on the existing evidence base and can be used in decisionmaking for transportation planning and assessment. We emphasize the importance of understanding the connectivity and relationships among different parts of the transportation system and all possible hazards, and how that knowledge, when used to make decisions, can not only lead to a more resilient transportation system but can also promote wellbeing in other socio-economic systems. This conceptual framework should be reviewed by transportation planners and policymakers for practical planning and decisionmaking considerations in the different systems.

This and the next two chapters are organized as follows. First, we discuss our conceptual framework by defining the transportation system and how it fits within a system-of-systems, a list of all possible hazards that a transportation system could face, followed by the resilience capacities and how they can be used as the key levers or devices when deciding on changes to the system through targeted investments, which can enable a more resilient transportation system. This discussion is then followed by a discussion of metrics that can be considered for transportation resilience, and finally, relevant considerations for how this conceptual framework and measurement can be applied more specifically to MPOs and state level transportation planning organizations.

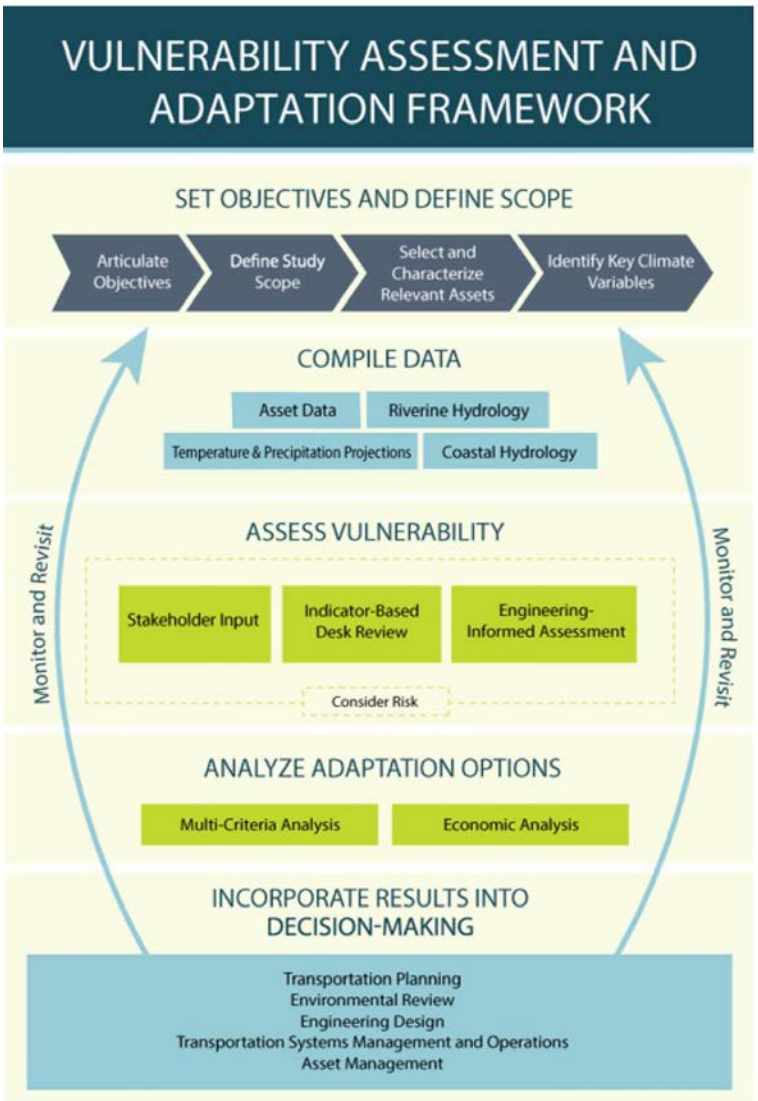
The Transportation System in a System-of-Systems

One of the challenges in developing a coherent definition and conceptual framework for the transportation sector is that the transportation sector is but one system in the system-of-systems that makes up the larger socio-economic system. Additionally, transportation is a means to an end and not an end in itself. People use the transportation system to access economically, socially, and environmentally valuable locations. Overlaying these ideas on a more traditional characterization of resilience may cause some contradictions or miss key aspects of the value of the transportation system in times of stress or shock. Therefore, our approach to a conceptual framework for better integrating the ideas of resilience into the transportation system is to recast the objectives of resilience in terms of transportation related concepts. This recasting will allow transportation planners to more easily incorporate the ideas of resilience into long term system wide planning and the decision-making process.

The FHWA VAF provides state DOTs and MPOs with a guide for how they could incorporate vulnerability to climate change and extreme weather events into their planning, vulnerability assessments. By highlighting project and program level steps that could be taken. It is a resource that provides a plethora of information on assessment methods to consider, data to

use, and what other transportation organizations are doing in this space, with a specific focus on hazards associated with climate change and extreme weather events. We use the VAF as a starting point for incorporating resilience more broadly into transportation planning. The VAF guides planners in making decisions that may reduce vulnerability, as illustrated in Figure 3.1.

Figure 3.1 FHWA Vulnerability Assessment and Adaptation Framework Conceptual Diagram



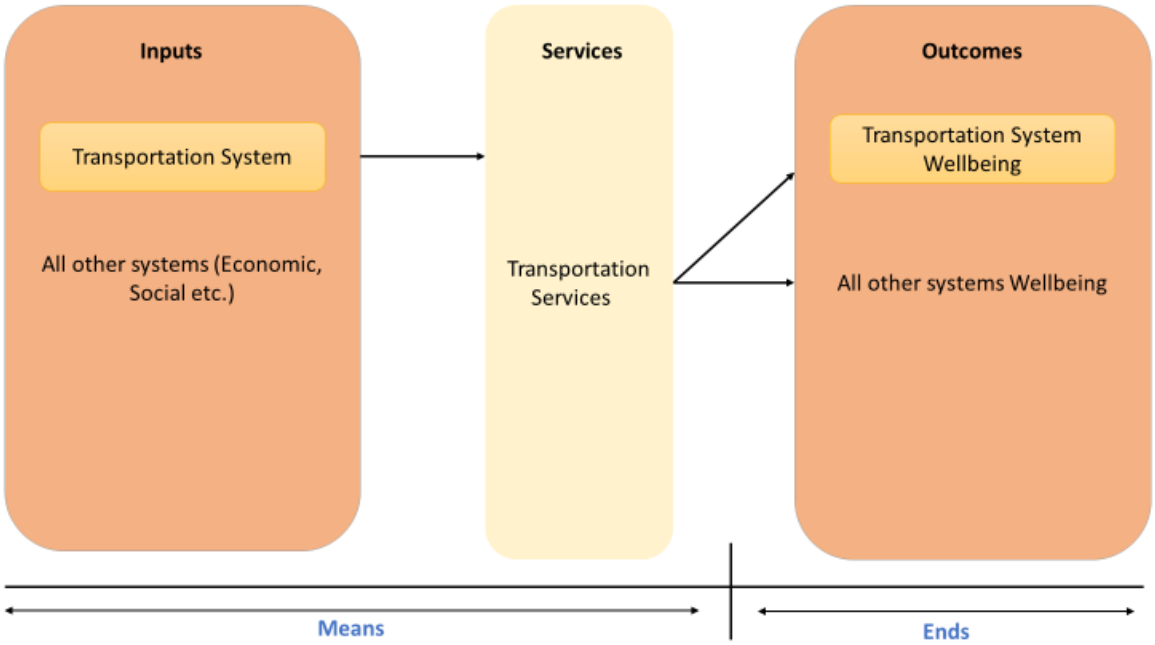
Source: https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/diagram_fullsize.cfm

In this report, by broadly defining the transportation system in a system-of-systems framework, we expand the VAF to allow a broader set of hazards and an alternative framing to better incorporate resilience principles. The approach we discuss considers all types of hazards and vulnerabilities to the transportation system as well as all types of benefits and intended outcomes that a resilient transportation system would provide as well as the outcomes in other systems that would result from a more resilient transportation system.

First, based on the findings discussed in the two previous chapters, as well as with information from stakeholders, we define a resilient transportation system broadly as one in which the transportation system contributes to the long-term wellbeing of the community. We use the term "wellbeing" to describe the continued functioning of the transportation systems which, in turn allows the social, economic, and environmental systems to continue to function in an undisrupted fashion. We see a difference between a resilient transportation system and a non-resilient transportation system. The difference is that the goal of a typical transportation systems to achieve and maintain a functioning system and maintain business as usual, whereas a resilient transportation system maintains normal functioning in usual circumstances *as well as* in times of stresses and shocks to the system. This goal is achieved by identifying critical elements of the transportation system and providing each asset within the system the capacity to achieve levels of functioning in times of system stresses such as high levels of congestion, or in times of shock such as an extreme weather event or a human-induced shock such as a cyber-attack on the transportation infrastructure. Importantly, critical elements of the system are exposed to a variety of hazards to which it must be able to respond using the capacities within the system.

When a resilient transportation system functions appropriately, both in normal circumstances and in times of stress or shock, the social, economic, and environmental systems continue to operate smoothly. When these systems continue functioning, they continue to produce certain benefits, and costs do not increase. These are a result of the outcomes of the transportation system. As Figure 3.2 illustrates, the transportation system, a known system within a larger system in a given geographic area, uses transportation services as a *means* to achieve the wellbeing of the transportation and other systems, otherwise known as the *ends*.

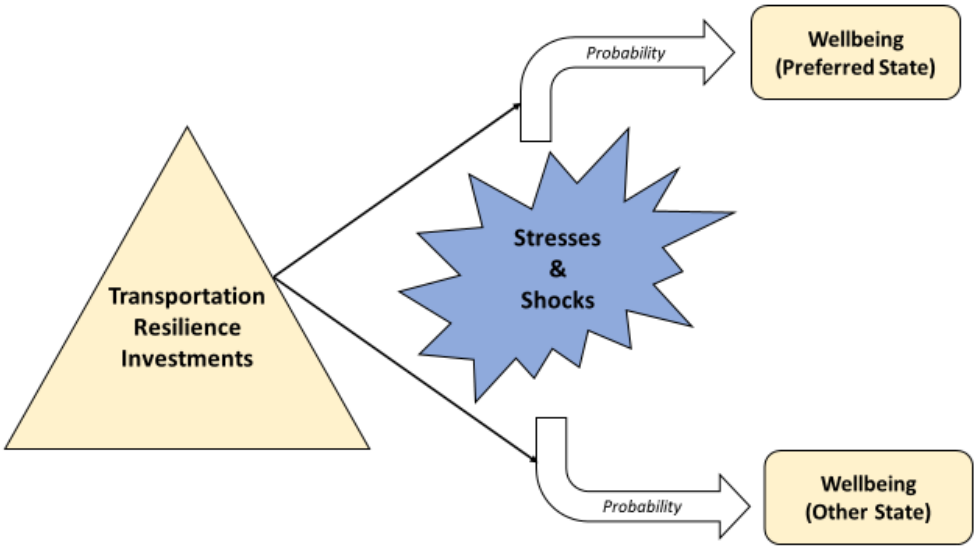
Figure 3.2 Transportation System as a Means to Ends



Source: Authors' Characterization

In addition, when resilience is considered in this system-of-systems approach, the benefits of changes in prioritized or increased investments in the transportation system will more likely increase the probability that the transportation system stays at or near a preferred state of wellbeing. In this case, we say that the system is more resilient. This idea is illustrated in Figure 3.3. If one investment provides greater resilience-enhancing benefits to a stress or a shock than another, then that investment provides a positive outcome, making the system more resilient, and resulting in a preferred state with increased probability. However, if no targeted investments are made or the investments are poorly planned, the result may be a less optimal state of wellbeing.

Figure 3.3 System Wellbeing derived from Changes in Probabilities of the System



Source: Authors' Characterization

How does this concept then contribute to understanding what is needed in a transportation system to get to the preferred state of functioning? How do we identify the investments that really matter to a given planning organization and how do we know those investments are working? To help answer these questions, we use the following sections to define the main characteristics of the transportation system, the expected hazards the system may face as well as the capacities needed to address any stresses or shocks caused by the hazards that promote resilience in a transportation system, which is embedded within the larger socio-economic system.

What Is a Resilient Transportation System?

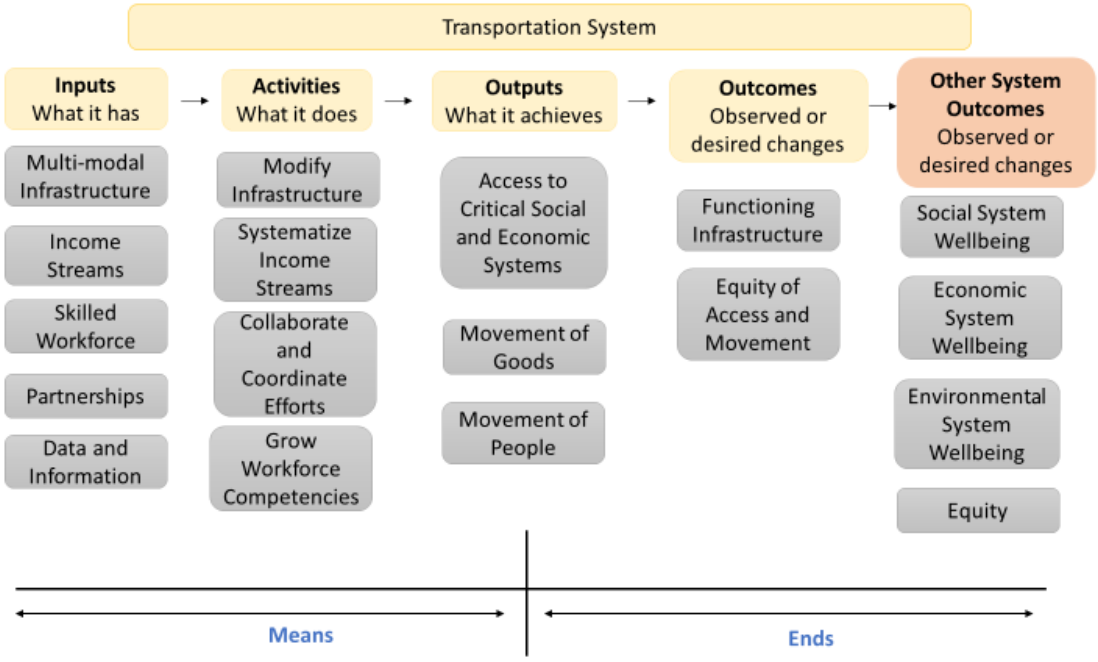
To understand the resilience of the transportation system and how to increase the probability of achieving a preferred state of well-being, we describe here what we mean by the "transportation system." We provide a conceptual mapping of the system to be able to discuss the outcomes of the transportation system, as well as the outcomes of the social, economic, and environmental systems as a result of the inputs, activities, and outputs that are derived from the transportation system.

While we understand that every transportation planning organization has its own unique structure, our conceptual framework includes certain inputs and actions (*means*) that we see as essential to achieving outputs and outcomes in a more resilient transportation system, as well as functioning greater social, economic, and environmental systems (*ends*). Figure 3.4 shows a

frequently used logic model method[9] for all transportation planning organizations to consider using for decisionmaking. We understand that some transportation planning organizations may already be considering such models, but we describe this conceptual framing in detail, including the main elements of the transportation system we see as linked to achieving greater resilience in a comprehensive system-of-systems approach.

Moving left to right, Figure 3.4 lists first the inputs, i.e., the transportation system's resources, followed by the activities the system conducts with those resources to achieve certain outputs or direct results of the activities. These outputs then lead to higher level outcomes, actual system achievements, including desired or observed changes for both the transportation system and in the context of a system of systems, the other social, economic, and environmental systems we mentioned. As noted earlier, the left side of the figure can also be considered the elements of the system that are the means that contribute to the ends found on the right side of the figure. We illustrate that outputs can be both ends but also means that contribute to the broader level outcomes.

Figure 3.4 Transportation Inputs, Activities, Outputs, and Outcomes



Source: Author's Characterization

[9] For more examples of logic model use, see footnote #1 in Savitz et al., Scott, Miriam Matthews, and Sarah Weilant, *Assessing Impact to Inform Decisions: A Toolkit on Measures for Policymakers*, Santa Monica, Calif.: RAND Corporation, TL-263-OSD, 2017. As of February 27, 2019: https://www.rand.org/pubs/tools/TL263.html.

Transportation System Inputs

Transportation system inputs include five main types. One, that we discuss the most in following chapters is multi-modal infrastructure, which includes a suite of assets: highways, local roads, and rail (not only for drivers but also for autonomous vehicles), and other gray infrastructure and green infrastructure such as pedestrian pathways, not only for walking but also for other modes such as bikes, scooters, and powered wheel chairs in a given geographic area for transportation of goods and people, operated by users of public transportation and private vehicles.

The transportation system also has a skilled workforce to accomplish planning goals. These individuals include planners, engineers, construction staff, operations staff, public transportation providers such as bus drivers or train conductors, and policymakers.

The system must have guaranteed streams of funding, either from federal, state, or local levels, but also including all possible revenues collected from sources such as tolls and gas taxes at rates that match current needs.

In addition, it is essential that the transportation system have formal partnerships—with clearly defined missions and collective objectives—with traditional and non-traditional entities and organizations who may influence transportation investments. These entities include public works, port authorities, freight providers, construction industry, chambers of commerce, hospitals and other medical centers, the environmental and social science community, law enforcement, emergency service providers, the private sector such as building and land developers, energy supply companies, educational institutions, community influencing organizations (faith-based organizations, community centers), advocacy and lobbying groups, and government officials. The ease of partnerships may be influenced by different business models. For example, the partnerships may be easier for MPOs who are hosted by other agencies than for independent MPOs to form. As one study by the federal highway administration found, hosted MPOs allow for enhanced coordination and effort, more financial assistance, and lower operational costs, but they may face greater challenges of autonomy in decisionmaking (Kramer, 2017). These touch points across other systems are imperative when considering the transportation system as a system in the broader system-of-systems.

Finally, the system should have relevant, useable data and information available on critical aspects of the transportation system such as congestion, network chokepoints, infrastructure assets, roads, bridges, and tunnels that are vulnerable to risk. Information is also needed on the social system, such as education, health services, and economic systems (such as businesses with which it interacts in a given geographic area and bordering jurisdictions) to understand the criticality and user base for different transportation system components.

Transportation System Activities

With the five types of inputs described, four main actions or activities can take place to achieve certain outputs in a functioning transportation system. One such activity includes targeted and prioritized changes and modifications to the transportation infrastructure with consideration for land use and private sector actions and their impacts on the transportation infrastructure. These modifications include those linked to hardening and adapting infrastructure, such as adding, moving, or raising roads and adding culverts or pedestrian pathways, with the goal of allowing continued movement in the face of any stresses, risks, or vulnerabilities during a shock.

Making these changes requires a workforce that increases its competencies in the transportation system through training and professional development. Also, assessing the available funding streams can be accomplished by the skilled workforce to determine where changes would best be targeted. For example, funding may need to be diverted to increase resilience of particular infrastructure assets to specific risks. By investing in peoples' skills within the system, the workforce can better ensure business as usual and aid in planning and executing responses to stresses and shocks.

With collaboration and coordination among partners, the funding streams and decisions about changes to the multi-modal infrastructure may better target aspects of resilience, especially where there is jurisdictional overlap of infrastructure. Collaboration and coordination can be done well when the transportation system and its partners have mutual goals and outcomes they would like to achieve.

An increased diversity in partnerships can also help all parties understand what non-traditional partners may change in their planning and decisionmaking to reduce certain stresses on the transportation system. For example, if a privately-run building development company is going to construct a residential building next to a critical transportation asset such as a major road, the building developer can better coordinate about land use through discussion and information sharing with the transportation partner to ensure continued mobility on that road. Including considerations like hydrologic factors, knowledge of floodplains and water run-off, and drainage can ensure that after a rainfall, the roadway is not flooded, which also decreases the possibility for congestion. As discussed in previous chapters, those who benefit from the transportation system, including the users, can be informed by the transportation planning workforce as well as relevant partners about important data and information regarding stresses such as closed roads or other critical factors that can affect their access to and movement within the transportation system.

Transportation System Outputs

In an ideal system, both the inputs and activities will achieve three main outputs. The first output will be access to critical social and economic systems. The transportation infrastructure

provides access for people to critical nodes or destinations within the network in a given geographic location. Those nodes lead not only to jobs, childcare, healthcare, education, leisure activities, and law enforcement, but also to social networks, and social support communities such as families and friends. Access to desired destinations, that is, the "physical access to places," is provided through different modes and alternate routes of the multi-modal system (GICD, 2017).

Second the transportation infrastructure, such as roads and freight, provides movement of goods of all kinds, —for example, food, construction materials, and medical supplies—to critical locations on time.

Third, the transportation infrastructure provides transportation system users movement, or safe, flowing mobility (absent congestion) to and from their desired destinations.

Transportation System Outcomes

The direct outputs from transportation system activities lead to two main outcomes in a resilient transportation system. The first outcome is that when access and movement are achieved, the transportation system functions normally. In other words, the desired results or outcomes of all elements in the first three columns in Figure 5.4 (inputs, activities and outputs) succeed at maintaining normal functioning within a given geographic area of responsibility. In addition, even in the face of a stress or shock, levers (choices, actions and capacities) are in place that still allow the transportation system to function normally, with minimal interruptions. Each element of the inputs, activities, and outputs can provide different benefits; for example, as Burkhardt and colleagues (2003) note, coordination with partners might result in more visible, higher quality transportation services, enhanced mobility, and more funding sources and cost savings opportunities.

The other main outcome of the transportation system includes equity in the form of access to movement for all individuals, including the socially vulnerable or economically disadvantaged, such as those in low-income areas, and those with special needs such as young children, the elderly, and those with certain medical conditions, among others. We recognize that the term "equity" can have many different contexts, and different phrases can mean similar things. Manaugh and colleagues (2013), who refer to this concept as social equity in the transportation system, reviewed several transportation plans goals, objectives, and related measures. The goals they identified often stated ideas like "better access for all," "increase transportation alternatives," and "accessibility and mobility for all." Based on these ideas, we refer to equity as an outcome of achieved access and mobility where options are available not only to the socially vulnerable but also to those who may be geographically distant or remote from important transportation infrastructure or previously lacked real options such as public transit with economically feasible fees for service, community led ride share services, or personally owned vehicles for accessing or using transportation infrastructure. Collaboration and service provision for all populations are important elements of the system that contribute to this type of equity.

Other System Outcomes

The final column on the right in Figure 3.4 notes that other transportation outcomes exist and have direct relationships to social, economic, and environmental system wellbeing in the given geographic area. The reason is that this level of system-of-systems outcomes represents the truly achievable ends of the activities invested and the outputs and primary outcomes (the means). These means, as noted in Figure 3.2, are the transportation system services and outcomes—a functioning transportation system—and the ends are that all other systems continue functioning. In the social system, desired outcomes would include, for example, individuals being able to access and to move safely to destinations where they can interact with their social networks and receive the needed services at medical centers, education institutions, and libraries; access shopping areas for essential and non-essential items, and also access areas that contribute to wellness such as parks and greenspaces. For the economic system, outcomes include businesses and governments being able to continue providing their own services, the people having access to their jobs, and transportation systems ensuring that goods reach their final destinations. For the environmental system, the outcome of interest (wellbeing) is achieved when the transportation infrastructure does not disrupt natural processes such as direction of water run-off, protection of certain ecosystems like wetlands, and limitation of the possibilities for erosion or flooding. Other related outcomes include increased use of greenways, pedestrian modes, and public transit (which can enhance air quality by reducing greenhouse gas emissions (Ngo et al, 2018) and pollution), and, using environmentally friendly construction materials, or devices like flow-through planters.

Finally, in systems that are able to continue functioning, equity can be achieved. Here, we use equity in the broad sense, meaning that all individuals have access to what they "need to survive or succeed—access to opportunity, networks, resources, and supports—based on where we are and where we want to go" (Putnam-Walkerly et al, 2016).

We acknowledge that not all the elements in Figure 3.4 may be new ideas, elements, or relationships to transportation planners. We simply wish to present a new way of thinking in which each element is leveraged in a way that may differ from current use of these resources and therefore contribute to newer, more resilient, transportation system ends. Now that we have explained the conceptual items necessary to achieve a more resilient transportation system, we will briefly discuss the possible hazards to transportation systems and then discuss what aspects of resilience can be used to achieve wellbeing (Figure 3.3). Specifically, we now describe the capacities needed to improve the resilience of the system.

What this System Means for Resilience and What is Needed

Understanding Hazards

Clearly some elements of the transportation system can improve resilience. To make more informed decisions, planners and decisionmakers must also be aware of the hazards that are most likely to cause stress or shock in their geographic areas. Based on stakeholder discussions and the literature review, we summarize the hazards that transportation systems may face (Table 3.1). This table lists additional hazards independent of weather and climate which the FHWA VAF focuses on. It is important to consider potential occurrences other than natural hazards when planning and investing in resilience efforts.

Table 3.1. Potential Hazards to Resilience

Categories of Hazards	Hazards
Natural, Environmental, Climate Change and Extreme Weather Events	Avalanche
	Drought
	Earthquake
	Erosion
	Extreme Heat
	High Wind
	Increased Precipitation (Rain, Snow, Ice)
	Landslide
	Hurricanes
	Tornados
	Rockfall
	Sea Level Rise
	Storm Surge
	Temperature fluctuation
	Wildfire
Human-Induced	Adverse Actor Physical Threat
	Autonomous Vehicles
	Congestion
	Cyber Attack
	Driver Human Error
	Population Growth
	Toxic/Flammable Substance Exposure

Source: Authors' interpretation

Planners must try to improve the resilience of transportation investments to the most likely hazards in their areas. Targeting efforts has the potential to significantly reduce the impacts of

the shocks that result from these hazards. Transportation planners also currently focus on some hazards that are unavoidable, such as climate change or an extreme weather event. However, some hazards such as congestion, or cyber or physical attacks to the infrastructure by adverse actors may be avoided or their impacts reduced with a thorough understanding of particular elements of the transportation system (Figure 3.4) and how investment in those elements can play a role in hazard avoidance. As Zimmeran et al. (2017) note, if cyber-attacks are not averted, "social and economic effects of cyber and physical security breaches can be widespread...They have economic impact on industry and workers, disrupt supply chains, and impact social services. Cyber–physical security breaches impact recovery time, which is a key resilience factor." These cascading effects outside of the transportation system are important to consider given the transportation system is a *means* rather than an *end* within the larger socio-economic system.

Having described the elements of the transportation system, their connectivity to other systems, the hazards those systems may face and the possibility of reducing the impacts in order to achieve a preferred state of wellbeing, we will shift to other capacities that can help the system achieve greater resilience and therefore greater wellbeing as a system.

Resilience Aspects

As discussed in Chapter 2 and Appendix B, Bruneau's framework characterizes a resilient system as follows:

- Reflective: Continuously evolving
- Robust: Anticipation of potential failures
- Redundant: Spare capacity to accommodate disruption
- Flexible: System can change, evolve, and adapt
- Resourceful: Alternative approaches are available
- Inclusive: Equity and community responsive
- Integrated: Integration and alignment across system

It may be difficult to think of these seven characteristics within a transportation context. For example, the concept of a reflective transportation system may not make sense. While transportation infrastructure is changing, the transportation itself is not evolving but rather absorbing and adapting to changes. As such, we map some of the characteristics from Bruneau's framework to capacities that may be more applicable to the needs of the transportation planner for decisionmaking. We call this the AREA interpretation of resilience:

- Absorptive Capacity
- Restorative Capacity
- Equitable Access
- Adaptive Capacity

To be clear, when we say absorptive capacity, we are referring the ability of the system to absorb shocks and stresses and maintain normal functioning. Restorative capacity is the ability of the system to recover following a shock or stress quickly and to return to normal functioning. Equitable Access is the ability of the system to provide the opportunity for access across the entire community during a shock or stress and during undisrupted times. Adaptive capacity is the ability of the system to change in response to shocks and stresses to maintain normal functioning.

Importantly, these AREA capacities represent alternative investment strategies that should be considered when considering increasing the resilience of the transportation system. That is, it may be more cost effective to invest in adaptive or restorative capacity than absorptive to maintain system functioning in normal and disrupted times. Though for equitable access, there may not be quite as close a substitute as for the other three.

To put these capacities into perspective for the transportation planner, here are a few examples. Investments in absorptive capacity could be investments in "hardening" the transportation infrastructure such as building a flood wall to reduce the probability that a road is flooded or more green infrastructure investments that change the drainage pattern around roads. Investments in restorative capacity could be investments in equipment, crews, and partnerships together with different incomes stream so that the infrastructure is repaired more quickly following an event. Investments in equitable access could include increasing transit service, such as by increasing the number or frequency of bus lines across the entire community or providing multimodal access to all including vulnerable and remote populations. Adaptive capacity investments may consist of adding roads that provide redundancy to other roads so as to provide additional capacity in the system to handle more traffic, reducing potential congestion during disrupted and normal conditions. Each of these capacities provides alternative means to achieving the end goal of a resilient transportation system. The capacities are also context dependent. There are different communities and geographic areas with different preferences and strategies for improving the resilience of the system depending on the levels of the capacities and relative costs of different strategies for increasing the resilience of the system.

We have discussed these capacities are at a systems level but since the transportation system is inherently a network the AREA approach could be applied to sub-systems within the transportation system or to the assets themselves in the system. Understanding this network nature of the transportation system and how these capacities are realized in such a system is paramount to identifying strategies for long term investment going forward. The CDOT study referenced earlier in Chapter 3 provides a starting point for considerations of the criticality of different components of a transportation system and how these components are exposed to varying degrees to multiple hazards. In the next section we expand on the idea of criticality.

Recasting of Resilience in a Network Context

As discussed in the literature review, many of the resilience frameworks are embedded within a system-of-systems framework. What makes the transportation system different than

most other systems is the network context that underlies the entire transportation system. As such, there are system-wide considerations of resilience together with the considerations of resilience of assets of the system and how they interact. That is, transportation resilience is a system level concept that is realized through the individual thoroughfares that make up the system. In particular, we cannot talk about resilience without talking about two important aspects of criticality and exposure. It is not just the vulnerability of the system to the exposure of a suite of hazards but how disruptions in one area of the network can "cascade" or spillover to other areas of the network. Thus, it becomes important to better understand the criticality of different assets of the transportation system.

For CDOT (Flannery et al, 2017), a measure of criticality is constructed using metrics of traffic flow, asset capacity and proxies for the value of goods and services that are flowing on the roadway, but criticality also includes metrics of social vulnerability for the population surround the road and a proxy for redundancy. Thus, segments that connect economically and socially important areas with sufficient traffic capacity, provide access to socially vulnerable populations, and have few alternative routes are considered critical according to the CDOT criticality index. In essence, criticality is how important the segment is to the movement of goods and people while simultaneously provide access to vulnerable populations. This is consistent with the definition of criticality used in other contexts.[10]

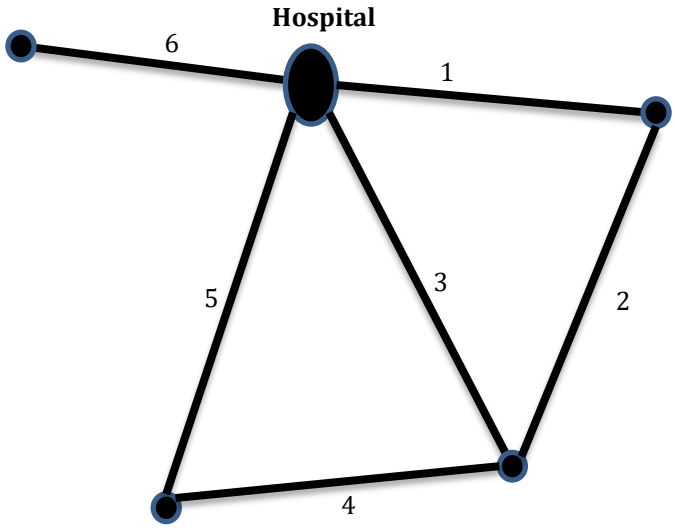
The criticality of an asset of the transportation system determines the size of the impact on the system if that asset is disrupted. When a critical asset of the system is disrupted, there are cascading effects in the network that cause further disruptions to take place. The criticality of the assets together with the exposure of these assets to the suite of hazards determines the resilience of the system. That is, a resilient transportation system is one in which critical assets are not exposed to hazards or, if so, that there exists sufficient absorptive, adaptive, restorative, or equitable access to mitigate the impacts of a shock. It is important that the criticality of the assets together with the exposure to different hazards be taken together when considering planning for a more resilient transportation system.

As an example, consider the system illustrated in Figure 3.5 and described in Table 3.2 in terms of which links are critical and at risk of exposure to a stress or a shock. In this system the most critical node within the system is the node where the hospital is located. In this case, it may be that the links (transportation infrastructure) numbered 1, 3, 5, and 6 in the figure are critical to the system functioning because of their connection to the hospital. But because there is considerable redundancy (additional or alternate routes) in the system through links 2 and 4, the criticality of each of 1, 3, and 5 is reduced. Suppose, further, that only links 3, 4, 6 are exposed to hazards. This suggests that the absorptive, adaptative, and restorative capacities of link 3 should be expanded to increase the resilience of the system. But that the resilience of link 6

[10] See for example: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2

could be expanded through additional redundancy in the system by adding an additional route to connect it to the rest of the network and not solely by hardening or increasing the absorptive capacity. This further suggests that the equitable access of link 6 may also need to be considered since the opportunity for access is easily denied for those located along link 6.

Figure 3.5 Conceptual Network Infrastructure and System Nodes



Source: Author's Characterization

Table 3.2 Conceptual Network Infrastructure Criticality and Exposure Mapping

Asset	Critical	Exposure
1	✓	X
2	X	X
3	✓	✓
4	X	✓
5	✓	X
6	✓	✓

Source: Author's Characterization

Importantly, in this network context, we are using the AREA interpretation, with the known criticality and exposure of the network to consider where future investments may need to be made. Using the AREA interpretation provides a means for exploring how alternative investments to reduce criticality and exposure can be used to increase the resilience of the system rather than simply focusing on hardening the system. Additionally, criticality of different assets

and how they are distributed across the community, including the socially vulnerable provides a means for understanding equitable access to the transportation system. Long-term transportation planning needs to consider the suite of available options for investment by using the AREA interpretation of resilience to lower the criticality and exposure across the system. By doing so, this will improve the functioning of the system in normal as well as disrupted times increasing the probability of a preferred state of transportation system wellbeing as illustrated earlier in Figure 5.3. The benefits that accrue during normal operations or business as usual, may outweigh those benefits that only occur during times of stresses and shocks. Thus, by choosing across the suite of potential projects consistent with the AREA interpretation, cost-effective improvements can be made that improve the overall function and resilience of the transportation system.

Summary

In this chapter, we have discussed a conceptual framing of the transportation system including the elements of the system using a logic model, the possible hazards to that system, as well as the capacities (AREA) that can be considered for changes to critical parts of the system to achieve greater resilience. Using the AREA approach to resilience may provide transportation planners with a framing that allows for a greater transparency of resilience in developing and choose alternative investment strategies for long term planning. This conceptual framing will help guide the implementation of the FHWA VAF in Chapter 5 to include a greater emphasis on resilience to a large set of hazards that are not necessarily associated with climate change.

In Chapter 4 we move to a discussion of why using metrics to assess the resilience of the system is important to enabling policymakers and planners to articulate precisely what the system includes and what the impacts of shocks would be, to inform planning and investments.

4. Ways to Measure Resilience

As explained by the AREA interpretation, resilience is a multifaceted concept. This means that there is no single metric or value that can perfectly reflect all aspects of resilience in all elements of a given system. Instead, decisionmakers must look at a wide variety of metrics to assess and understand the performance or impacts of the investments they make through AREA to improve the resilience of their assets within the transportation system. This chapter provides guidance on how to measure the resilience of transportation systems by presenting a wide variety of quantitative and qualitative metrics that can be used to measure the distinct system capacities discussed in the AREA interpretation while also considering what elements of the system contribute to reduced exposure to all types of hazards natural or human-induced.

Metrics for Resilience

Before discussing metrics in detail, it is important to remember that resilience is an abstract concept yet expected to result in tangible outcomes listed in Chapter 2. Assessing resilience requires, first, explicitly defining the desired level of service the transportation system should be able to maintain when faced with specific hazards that result in stresses or shocks. For example, a transportation system in the northeastern United States might desire to have a resilient system that continues to function and enable all users to reach their desired locations with minimal delay during a snow storm that drops up to six inches of snow over the course of 4 hours. A system that can maintain functioning during a particular stress or shock is considered a resilient system. As discussed previously, resilience requires identifying the shocks and stresses to which the system should be resilient. The general statement that the transportation system should be "resilient," such as noted in the literature and stakeholder interviews, is usually an implicit statement that the system should be resilient to a broad suite of shocks that are relevant or likely to affect the system. It is impossible for a system to be resilient to all imaginable shocks, so to be more precise, rather than simply calling a system "resilient," the system should be referred to as "resilient to [the desired suite of shocks]."

Impacts of hazards, and the stress or shock they produce, can be reduced through considering AREA as noted above, and by measuring those impacts as a result of targeted investments. Using this process, planners and decisionmakers can continue to improve investments over time making the system more resilient to a wider variety of shocks and stresses that are relevant to their specific transportation system infrastructure and network.

Metrics in general help transportation planners inform plans, decisions and assessments to understand whether their system will likely meet desired level of resilience when faced with a variety of stresses and shocks (Savitz et al, 2017). Second, repeated measurement of the same

metric over time can support decisionmaking by helping transportation planners understand whether and how policies are improving the resilience of their system (Yee and Niemeier, 1996). Which metrics are most important to use or improve depend on the type of stress or shock, and level and type of service or critical part of the transportation system planners are trying to maintain. For example, increasing the availability of alternative routes or alternative mode choices may be the best choice for increasing resilience against certain types of shocks, while improving the reliability of major thoroughfares may improve resilience against other types of stress or shocks. Identifying the appropriate metric requires considering the needs and context of each network and individual sub-system setting and the goals of the planning organization. The approach of this chapter is to present a variety of options of metrics from which transportation planners can consider applying to their own transportation systems.

These metrics can be useful for tracking progress in achieving the investments through AREA capabilities of different elements of the transportation system that are listed in the logic model above in Figure 3.4. Metrics based on existing or desired data and information can be mapped to each element of the logic model to help planners clarify exactly what they are measuring as well as identify what gaps in measurement may exist. Broadly, metrics for inputs track the resources that currently compose a transportation system, and the status of those resources. Metrics for activities track the actions being taken within the transportation system. Metrics for outputs measure the performance of the transportation system itself and may be directly altered through the activities. Metrics for outcomes measure the transportation-related experiences of system users. In some cases, transportation planners may want to also measure outcomes in other social, economic and environmental systems, which result from transportation services such as economic development or jobs by location.

Measuring Resilience at Each Step of the Transportation Framework

The remainder of this chapter provides examples of metrics that can correspond to each step of the logic model discussed in Chapter 3. We separate metrics for inputs and activities according to the capacity to which each metric corresponds. We then discuss metrics related to outputs and outcomes. Table 4.1 shows how categories of metrics map to relevant steps of the transportation system logic model in Figure 3.4 and AREA capabilities. Specific metrics within each general category are discussed further below. A single specific metric may map to different steps of the logic model or multiple AREA capabilities.

Table 4.1: Metrics for Measuring AREA

Step of Logic Model	AREA Category	Categories of Metrics

Inputs	Absorptive Capacity	Exposure metrics
	Restorative Capacity	Available Response Resources
	Equity	Availability of public transit; Availability of alternative mode choices
	Adaptive Capacity	Availability of alternative routes and alternative mode choices
Activities	Absorptive Capacity	Maintenance metrics
	Restorative Capacity	Measures of community planning efforts; Measures of communities' communication capabilities
	Equity	Measures of communities' communication capabilities
	Adaptive Capacity	Network expansion
Outputs	N/A	Intensity of Route Use or Vehicle Miles Traveled; Measures of transportation system's state of repair; Reliability Metrics;
Outcomes	N/A	Measures of congestion, travel time, and travel speed; Measures of transportation system safety; Reliability Metrics; Accessibility metrics

Source: Author's Characterization

The following descriptions of specific metrics are not an exhaustive list of the metrics planners should consider but are rather exemplary of the items planners should be considering in their own systems to make more informed decisions that contribute to a resilient transportation system. The metrics described in this section include some that are documented in Chapter 2 as well as new metrics for consideration.

Measuring Inputs and Activities

Inputs to the transportation system involve the location of transportation system components, the characteristics and status of those different components, and their exposure to risk. Inputs also include the income streams, workforce, partners, and data systems that support the transportation system. Transportation planners then engage in activities which alter those inputs to improve the ability of the system to provide transportation services. Different types of metrics may be used to measure how inputs reflect absorptive, restorative, or adaptive capacity and how activities improve those capacities. Equity is the distribution of access to those services. Below, we discuss different metrics for measuring inputs and activities related to each of these capacities.

Absorptive Capacity

As noted earlier, absorptive capacity refers to the ability of the transportation system to absorb shocks and stresses and maintain normal functioning. This capacity to absorb can be increased by "hardening" assets of systems or reducing exposure to risk. Based on the literature available, absorptive capacity in transportation is a better understood approach to resilience though not necessarily labeled as such. Because of this, there are a wide variety of metrics available to consider understanding what a given transportation system's absorptive capacity is within different elements of the system. Most of the discussion of this capacity addresses the multi-modal transportation infrastructure element of the logic model in Figure 3.4

For absorptive capacity, inputs involve understanding the exposure of the transportation system infrastructure to shocks and stresses. Discussion of such metrics can be found in Dix et al., 2018. Examples include the mileage of transportation assets located in high-risk areas for natural hazards such as floods, wildfires, or landslides. Exposures to risks beyond natural hazards, such as cyber risk, fleet changes, or policy changes, should also be considered. In addition to the transportation assets, measures of the number of destinations (including critical assets such as hospitals, energy production, transmission, or distribution, and schools) that are exposed to risk can be useful. In some cases, transportation planners may be able to explicitly measure the extent to which the transportation infrastructure can absorb shocks or stresses without a loss of performance, such as the percentage of transportation assets that can accommodate a rise in sea level or can continue to perform when the electric power grid is disrupted. For example, traffic lights might be equipped with backup power systems in the event of a power outage and be programmed to switch to flashing red lights if a cyber disruption interferes with their normal ability to regulate traffic flow. Planners should also consider the return periods of risks that are most relevant to their region.

Transportation systems frequently invest in activities to increase the absorptive capacity of their system. Again, discussion of such metrics for tracking investments can be found in Dix et al., 2018. Examples include the annual percentage of routine inspections or maintenance activities completed on time for all assets, or the quantity of weatherization repairs made each

year. Some metrics track preventative care and planning pre-stress or shock, such as the quantity of litter or debris removed from storm drains, culverts, or roadsides monthly, or the number of stormwater management improvements through facilities such as a watershed basin's ability to maintain a level of service and absorb the rainfall in a given area over a certain period of time[11] or the number of projects that raise the roadway grade. There may also be investments in the training of emergency response personnel, or investments in communication technology that alert users to changes in system conditions or availability.

Table 4.2: Sample Metrics for Absorptive Capacity Inputs & Activities

Step of Logic Model	Category	Sample Metrics
Inputs	Exposure metrics	Mileage of new facilities in Flood Zones - transit investments, bicycle facilities, streets, and bridges
		Number of highway lane and centerline miles within the 100-year floodplain
		Employment and housing in FEMA 100-Year floodplains
		Employment and housing in wildland-urban intermix areas (forest fire risk)
		the percentage of facilities that accommodate two feet sea level rise
Activities	Maintenance metrics	Annual percentage of routine culvert inspections completed on time
		Quantity of litter/debris cleared from storm drains/culverts/roadsides (reduce roadway flooding)
		Number of stormwater improvements

[11] See the 2008 Hillsborough, FL comprehensive plan for stormwater management for more details on their assessment and use of level of service measurement. Hillsborough County Stormwater Management, Future of Hillsborough: Comprehensive Plan for Unincorporated Hillsborough County Florida August 4, 2008. http://www.planhillsborough.org/wp-content/uploads/2012/10/STORMWATER_11_2012.pdf

		Number of projects that raise the roadway grade or increase resilience against climate change or natural disasters though other means

Sources: Author's Characterization, Dix et al, 2018

Restorative Capacity

Restorative capacity refers to the ability of the system to recover following a shock or stress quickly to normal functioning. This capacity can be increased by establishing disaster response plans and establishing quick-response capabilities. Restorative capacity is often thought of in term of responses to natural disasters, but the concepts can be applied broadly as responses to any form of disruption.

Inputs for restorative capacity measure existing capabilities to respond to shocks and stresses. These include measures of personnel and partnerships, such as counts of construction equipment and workers in the region. Inputs also include budgets, such as discretionary income available during emergencies, as well as physical resources specifically set aside for known disruptions such as snow, fire, cyber system disruptions, or congestion.

Having response plans in place can greatly improve the speed and effectiveness of efforts to restore transportation capacity. Some of this planning must be done by the transportation system operators, but the community of users themselves should also be aware of and involved in the planning process. Measures of community planning efforts can help understand how well prepared the community is for various disruptions. Measures discussed by the United Nations Office for Disaster Risk Reduction (2017) include the percentage of communities or neighborhoods with at least one "grass roots" non-governmental body for planning disaster risk reduction interventions and post-event responses, the frequency of these community organization meetings, attendance at these community organization meetings, and the percentage of communities or neighborhoods with community bodies that have clearly defined and supported roles in the response process. While "grass roots" organizations may be unable to replace the services provided by official organizations, their involvement may improve community engagement with post-event responses.

A related factor to measure is communities' communication capabilities. Even if the perfect plan is in place, it will not have the desired impact unless the plan can be quickly and effectively communicated to all users of the transportation system. Metrics that measure these communication capabilities include the length of time it takes to contact all community residents in the immediate aftermath of an event, the percentage of community residents that can be contacted within a given number of hours following an even, the percentage of employers that pass reliance communications to employees, and the number of different modes of engagement

for reaching community residents. These communication capabilities can serve roles beyond but including transportation, such as communicating what routes are open or closed during emergency procedures such as evacuations, or how various forms of public transit are responding to severe weather disruptions.

Table 4.3: Sample Metrics for Restorative Capacity Inputs

Step of Logic Model	Category	Sample Metrics
Inputs	Available Response Resources	Counts of construction equipment or workers in the region
		Budget for snow removal, fire suppression, cyber system protection, or other hazards
		Counts and maintenance status of snow plows or other emergency equipment
Activities	Measures of community planning efforts	Percentage of communities/neighborhoods with at least one "grass roots" non-governmental body for planning disaster risk reduction interventions and post event responses.
		Frequency of community organization meeting
		Attendance at community organization meetings (# of people)
		Percentage of communities/neighborhoods with community bodies that have clearly defined and supported roles in disasters
	Measures of communities'	Length of time it takes to contact all community residents in the immediate aftermath of an event

	communication capabilities	Percentage of community residents that can be contacted within 12 hours following an event
		Percent of employers that pass resilience communications to employees
		Number of different modes of engagement for reaching community residents

Sources: Author's Characterization; United Nations Office for Disaster Risk Reduction, 2017

Adaptive Capacity

Adaptive capacity refers to the ability of the system to change in response to shocks and stresses to maintain normal functioning. One commonly used set of measures involve the availability of alternative routes and alternative mode choices. These metrics can help understand the inputs that make up the current transportation system, and how well the system can continue to operate when segments of the network are closed, such as commonly occurs for repair and maintenance purposes. Measures of the availability of alternative route choices include the distance to alternative routes, the number of "reliable" routes, and measures of network density (such as block lengths or street miles per square mile). Discussion of alternative route choice metrics can be found in Parkany and Ogunye, 2016; Tierney and Bruneau, 2017; Nassif, et al., 2017; Governors' Institute on Community Design, 2017; Flannery, Pena, and Manns, 2018; and Twaddell et al., 2018. Ip and Wang (2011) develop a metric called "friability" which measures the reduction in network resilience as measured by the change in the weighted average number of reliable passageways with all other nodes in a network following a disaster, considering the population of the various nodes. Measures of the availability of alternative mode choices include the portion of low-income household income that goes towards transportation costs, the level of physical separation between traffic and pedestrians or cyclists, multimodal door-to-door travel time, rates of car ownership, the percentage of street-miles that accommodate non-motorized modes of transportation, and measures how mode split. Discussion of alternative mode choice metrics can be found in Pratt and Lomax, 1996; Venter, 2016; Governors' Institute on Community Design, 2017; and Twaddell et al., 2018. These metrics can be useful for helping planners understand the transportation decisions individual system users will make under normal and restricted conditions.

Transportation planners can use metrics to measure and track the implementation of projects that increase adaptive capacity. Examples from Twaddell et al., 2018 and the authors of this

report include tracking the percentage of planned additional mileage that has been completed, the number of alternative mode projects that have been implemented.

Table 4.4: Sample Metrics for Adaptive Capacity Inputs

Step of Logic Model	Category	Sample Metrics
Inputs	Availability of alternative routes and alternative mode choices	The distance to alternative routes
		Friability: "the reduction in network resilience as measured by change in the weighted average number of reliable passageways with all other nodes in a network following a disaster, taking into account the population of the various nodes."
		The number of reliable routes
		Network density (block lengths; street miles per sq mile)
		Ratio of percentage of transportation funding received by mode to the percentage of usage of mode
		The portion of low-income household income going towards transportation costs
		The level of physical separation between traffic and pedestrians/cyclists
		Measures of mode split
		Multimodal door-to-door travel time
		Car ownership rates
		Percent of street-miles with nonmotorized facilities

Activities	Network expansion	Percent of planned nonmotorized facility-miles that are complete
		Miles of planned nonmotorized facilities that have been built

Sources: Author's Characterization; Flannery, Pena, and Manns, 2018; Parkany and Ogunye, 2016; Tierney and Bruneau, 2017; Ip and Wang, 2011; Nassif, et al., 2017; Governors' Institute on Community Design, 2017; Twaddell et al., 2018; Litman, 2014; Pratt and Lomax, 1996; Venter, 2016;

Equity

Equitable access refers to the ability of the system to provide the opportunity for access across the entire community during a shock or stress and during undisrupted times. Equity is concerned not only with the transportation system itself, but with the ability of different populations to access the transportation system.

Measures of the availability of public transit include the percentage of region's population living and working within a given proximity to transit stops. This metric might be tailored to specific populations, such as the share of low-income households living within a half-mile of a high frequency public transit service. Such equity metrics are also concerned with the underlying population distribution across the region, including the distribution of vulnerable populations. Discussion of such metrics can be found in Nicholls, 2001 and Governors' Institute on Community Design, 2017.

Measures of the availability of alternative mode choices include the portion of low-income household income that goes towards transportation costs, the level of physical separation between traffic and pedestrians or cyclists, multimodal door-to-door travel time, rates of car ownership, and measures how mode split. Planners could also review how financial resources are currently distributed across modes and whether that distribution matches differences in usage rates. These metrics can be useful for helping planners understand the transportation decisions individual system users will make under normal and restricted conditions. Discussion of such metrics can be found in Pratt and Lomax, 1996; Venter, 2016; and Governors' Institute on Community Design, 2017.

Different groups might have differential access to the transportation system during times of shock or stress. Metrics such as heat vulnerability indices, as described in Madrigano et al (2015), can help highlight where sensitive groups are located in order to determine where access limitations might occur.

Communities' communication capabilities are measure of both restorative capacity and equity. The rapid and effectively communication of key information is important not only for restoring the functioning of the transportation system, but also for ensuring all users understand how to access and use the transportation system. For example, sensitive populations that rely on

public transit need to know if there are changes in the operation of that system during weather emergencies. At the same time, those sensitive populations may have access to fewer sources of information about the status of the system.

Table 4.5: Sample Metrics for Equity Capacity Inputs

Step of Logic Model	Category	Sample Metrics
Inputs	Availability of public transit	percentage of region's population living and working within close proximity to transit stops
		percent of total population in a given area including vulnerable populations served
		share of low-income households living within one half mile of high frequency transit service
	Availability of alternative mode choices	The portion of low-income household income going towards transportation costs
		The level of physical separation between traffic and pedestrians/cyclists
		Measures of mode split
		Multimodal door-to-door travel time
		Car ownership rates
		Percent of street-miles with nonmotorized facilities
Activities	Measures of communities' communication capabilities	Length of time it takes to contact all community residents in the immediate aftermath of an event
		Percentage of community residents that can be contacted within 12 hours following an event

		Percent of employers that pass resilience communications to employees
		Number of different modes of engagement for reaching community residents

Sources: Author's Characterization; Governors' Institute on Community Design, 2017; Nicholls, 2001; United Nations Office for Disaster Risk Reduction (2017); Pratt and Lomax, 1996

Measuring Outputs and Outcomes

Activities are aimed at increasing the AREA capacities of inputs in order to improve the well-being of transportation system users. The direct implications of these activities are measured as outputs – changes that occur in the transportation system as a result of the activities. These outputs are important because they result in outcomes – changes in access and experience for the transportation system user.

Outputs

Metrics for the intensity of route use measure the amount of movement along the routes in a given network or geographic area at various periods of time. Discussion of such metrics can be found in Venter, 2016; Governors' Institute on Community Design, 2017; and Dix et al., 2018. These metrics are useful for assessing the absorptive capacity for traffic flow and congestion, either as a stress to the system infrastructure or because of a shock. Some metrics might be specific to a road, route, or mode choice, such as include the number of people traveling on specific routes each day, the aggregate number of hours people spend traveling on specific routes each day, or the ratio of the volume of usage relative to the capacity. Transportation planners might particularly focus on changes in usage rates when an alternative mode or route becomes unavailable. The percentage of travelers that use alternative modes or routes (as opposed to cancelling or rescheduling their plans) can give a sense of the adaptive capacity of the system.

These metrics do not need to be limited to roadways. For example, transportation systems measure the number of public transit riders and usage relative to capacity of those systems and other alternative mode choices such as greenway use. Other metrics are broader regional metrics, such as the average daily inflow and outflow of workers in a region, or total vehicle miles travelled (VMT) within a boundary.

Measures of transportation system's state of repair can be important for understanding how easily a hazard or normal wear-and-tear of assets might result in significant reductions in service capacity. If the road conditions are not good, and a link or route in a network could be washed out or eroded during a shock, the service of providing access to destinations and movement of

goods and people may be reduced. Metrics that measure road surface conditions, such as the International Roughness Index, are a common example. There are also metrics for the condition of bridges, sidewalks, crosswalks, and bicycle infrastructure. These metrics help understand direct results of the current system services and what the infrastructure can or cannot absorb in terms of demand. This combined with metrics on a given road's closure time within the network will help planners understand how well the remaining routes can absorb the traffic flow that is shifted to those remaining functioning routes. Continued functioning of the transportation system even in a time of stress as an outcome is discussed in the next section.

Table 4.6: Sample Metrics for Outputs

Step of Logic Model	Category	Sample Metrics
Outputs	Intensity of Route Use or Vehicle Miles Traveled	Number of people traveling along/through route each day
		Number of hours people spend traveling along/through route each day
		Worker inflow and outflow
		Traffic colume/capacity ratio
		Number of public transit riders
	Measures of transportation system's state of repair	International Roughness Index (IRI)
		The percentage of roadways in "poor" or "fair" condition
		Pavement and bridge condition on the interstate system and on remainder of the national highway system
		Pavement and bridge condition on local roads
		Condition and availability of sidewalks, crosswalks, & bicycle infrastructure

	Reliability Metrics	Measures of resilience (Zhang et al. 2010)
		Truck Travel Time Reliability (TTTR) Index
		Vehicle delay

Sources: Author's Characterization; Governors' Institute on Community Design, 2017; Flannery, Pena, and Manns, 2018; Parkany and Ogunye, 2016; Tierney and Bruneau, 2017; Memphis MPO, 2016; Dix et al, 2018; Zhang et al., 2010; Jenelius, Petersen, & Mattsson, 2006; Chen & Miller-Hooks, 2012; Nassif et al., 2017; Texas Department of Transportation, 2018; Venter, 2016

Outcomes

Measures of congestion, travel time, and travel speed help measure how efficiently the transportation system moves users between locations under normal and restricted conditions. Discussion of such metrics can be found in Ewing (1993); Adams, Bekkem, and Toledo-Durán (2012); Hoogendoorn-Lanser, Schaap, and Van Der Waard (2012); Venter, 2016; Governors' Institute on Community Design, 2017; and Flannery, Pena, and Manns (2018). These metrics may be measured at an aggregate level, or for specific subgroups such as low-income households or households from specific regions of the network. Metrics include door-to-door travel times, average commute times, travel speeds for cars or trucks, hours of congestion, travel time indices, travel time reliability measures, and more qualitative "level of service" measures.

Metrics for transportation system safety assess the underlying risk associated with the transportation infrastructure system itself, including the day-to-day disruptions to which the system should be resilient. Measures of transportation system safety include the number or rate of transportation-related fatalities that occur each year in a given area or on a given route. Similar metrics can be used to measure transportation-related injuries, transportation-related accidents, alcohol-related accidents, or truck-related accidents. Other measures include the availability of safety or courtesy service patrols, the availability of street lighting, or the rate of seat belt usage.

A broad method decisionmakers could consider is to use longitudinal data, data that tracks the same thing at different points of time, to look at changes in metrics before and after an event. For example, Zhang et al. (2010) develop a framework for calculating measures of resilience (MOR). Specifically, they define MOR as:

$$MOR = \frac{(RI_{before} - RI_{after})(1 + t^{\alpha})}{RI_{before}}$$

Where RI_{before} is the value of a resilience metric before an event, RI_{after} is the value of the same resilience metric after an event, t is the total time required to restore the capacity (e.g. years), and α is a system parameter. Such metrics can be broadly thought of as identifying the reliability of the metric, as the reflect how much (or how little) the metric changes following a disruption. Other assessments of reliability look at changes in travel costs, travel time, or travel speed before and after an event. Absorptive capacity is concerned with keeping this change as small as possible, while restorative capacity is concerned with having any changes that occur return to normal operating levels as quickly as possible.

There are a variety of metrics that measure whether different populations have equitable access to resources. Cumulative opportunity metrics include the number of jobs or other destinations accessible by road or public transit within a given number of minutes. Like many metrics, they can be calculated for the population at large or for specific sub-groups. There are not standard values for the parameters – whether to assess the number of jobs available within 60 minutes or 30 minutes or some other value is a fairly arbitrary decision. One might adapt these cumulative opportunity and gravity metrics to measure the number of jobs or desirable locations accessible within a certain number of miles or certain amount of travel time if the particular elements of the transportation system are unavailable. Gravity measures seek to address the challenge of how to determine an arbitrary time or distance radius by discounting opportunities that take longer to reach or are a further distance away. Discussion of cumulative opportunity metrics and gravity measures can be found in Geurs and Van Wee, 2004; Fan, Gurthrie, and Levinson, 2010; Venter, 2016; and Governors' Institute on Community Design, 2017. Another prominent example of an access metric is the prevalence of "walkability score" metrics that assess how many desirable destinations are within a walk-able distance of a given location. Such metrics are popular and prevalent on sites that help individuals search for housing options. There are also utility-based accessibility measures that are derived directly from discrete choice models. Discussion of walkability scores and discrete choice methods can be found in Venter, 2016; Governors' Institute on Community Design, 2017; and Twaddell et al., 2018. The University of Minnesota's Accessibility Observatory hosts a variety of data and research on different accessibility metrics across a variety of U.S. cities.[12]

Table 4.7: Sample Metrics for Outcomes

Step of Logic Model	Category	Sample Metrics
Outcomes	Measures of congestion,	Car or truck speeds and car or truck counts – how much time passed from

[12] For more information about the University of Minnesota's Accessibility Observatory, see http://access.umn.edu/

	travel time, and travel speed	event start to minimum value, and minimum value to pre-event value
		Hours of congestion
		Travel time index
		Travel time reliability
		Average commute times for low-income households
		Roadway level of service – a qualitative measure expressing the quality of transport service from the point of view of the user and largely seen as a function of speed
	Measures of transportation system safety	Number (or rate) of transportation-related fatalities, injuries, or accidents that occur each year in a given area or on a given route
		Number (or rate) of alcohol-related incidents that occur each year in a given area or on a given route
		Number (or rate) of truck-related incidents that occur each year in a given area or on a given route
		Seat belt usage
		Availability of street lighting
	Reliability Metrics	Measures of resilience (Zhang et al. 2010)
		Truck Travel Time Reliability (TTTR) Index
		Vehicle delay
	Accessibility metrics	Number of destinations within walking/biking distance
		"Walkability Score"-style metrics

		Utility-based accessibility measures that are derived directly from random utility discrete choice models

Sources: Author's Characterization; Adams, Bekkem, & Toledo-Duran, 2012; Governors' Institute on Community Design, 2017; Flannery, Pena, and Manns, 2018; Venter, 2016; Ewing, 1993; S. Hoogendoorn-Lanser, Schaap, and Van Der Waard, 2012; National Academies, 2002; Tennessee Department of Transportation, 2015; Parkany and Ogunye, 2016; Tierney and Bruneau, 2017; Zhang et al., 2010; Jenelius, Petersen, & Mattsson, 2006; Chen & Miller-Hooks, 2012; Nassif et al., 2017; Texas Department of Transportation, 2018; Twaddell et al., 2018;

Other Metrics

In addition to the metrics discussed above that help measure the investments in AREA, there are several other metrics that are important to transportation planners to help them assess the impacts of their entire system. Savitz et al. 2017 notes "Reasoned analyses about why the values of measures are changing, or how they are likely to change if policies shift, need to consider the actions and reactions of other parties. They also need to incorporate uncertainty regarding both the present state and the future, to include both human dynamics and the natural environment." Metrics for such factors include greenhouse gas emissions, topography, and land use. Planners also care about identifying critical destinations that should be remain well-connected to the transportation network even in times of shocks or stresses.

Transportation systems are expensive to create, operate, and maintain. In many cases, transportation systems are financed through user fees. Those fees are designed to cover the costs of the transportation system, but individuals may value the benefits of the system beyond the costs of using or having access to the system. Housing prices and other costs may increase in proximity to highly desirable transportation systems as individuals seek to pay premiums to obtain easy access to the transportation system. This can create equity challenges, as low-income individuals that transportation systems are often targeted at serving may be priced out of regions where successful transportation systems are implemented. In theory, this pricing out should decline as desirable transportation systems become more widespread, but we are not aware of any empirical evidence on that topic. But given this problem, it is important to measure the cost of transportation and cost of living faced by transportation system users, particularly vulnerable or low-income populations. Examples of such metrics include measures of housing costs, the measures of single-mode or multi-modal transportation costs, and the change in travel costs associated with a shock or stress. Discussion of such metrics can be found in Jenelius, Petersen, and Mattsson, 2006; Chen and Miller-Hooks, 2012; Marshall, Henao, and Bronson, 2015; and Governors' Institute on Community Design, 2017.

5. Considerations for MPOs and State DOTs

As discussed previously, resilience is an abstract concept and approach to thinking about how a system-of-systems responds to different shocks and stresses. The FHWA Framework can be easily modified to broaden its application by decisionmakers by simply taking the AREA interpretation for resilience and using it to replace vulnerability within the overall framework.

Our main recommendations for implementation of the VAF to incorporate more resilience aspects are:

- Expand the objectives and scope to include shocks and stresses not directly tied to climate change, including cyber-attacks (See Table 3.1)
- Broaden the asset data to include human and equipment assets, using the logic model to guide expansions, and identify the criticality of these new assets (See Figure 3.4)
- Expand hazard data to consider a wider array of hazards and characterize whether the hazards is system wide or just influences a subset of assets (See Table 3.1)
- Use indicators identified in Chapter 4 to assess resilience of the system in a way that acknowledges the interaction of assets criticality and exposure.
- Engage stakeholders and decisionmakers when prioritizing options to help weigh tradeoffs that come with prioritizing options (See Chapter 2 and Appendix B)
- Utilize an established critique to facilitate the prioritization such as multi-criterion analysis, economic analyses, benefit-cost analysis, or life-cycle cost analysis. (See Chapter 2 and Appendix B)
- Consider the benefits of investment both in times of normalcy and times of disruption (See Figure 3.3)

To express these ideas more formally, we first summarize the six-step process involved in the VAF and how each step could be modified by state DOTs and MPOs to incorporate more resilience to multiple hazards at each step.

Vulnerability Assessment Framework

The VAF provides a six-step process to frame planning around mitigating and adapting to vulnerabilities in a transportation system. These six steps are:

1. Articulating objectives and defining study scope
2. Obtaining asset data
3. Obtaining climate data
4. Assessing vulnerability
5. Identifying, analyzing, and prioritizing adaptation options
6. Incorporating assessment results into decision making

Objectives and Scope

In this first step, the goals and boundaries of the study are defined. The scope and scale of an assessment is bounded by what assets the organization has control over as well which characteristics of those assets will be considered. In addition to the assets, defining what hazards will be considered as part of the vulnerability assessment. The VAF is specifically designed to consider climate change vulnerability but can easily be expanded to consider shocks and stresses that are not directly tied to climate change by state DOTs and MPOs. In particular, the inclusion of human-induced disruptions such as cyber-attacks can be incorporated into the scope of the study though it may be less straightforward how to assess the risk of cyber-attacks than to assess the risk of flooding where inundation maps exist. As discussed in Chapter 3, a broader set of hazards should be incorporated in to the scope of resilience. Table 5.1 (recreated from Table 3.1) provides a set of hazards that could be incorporated into the scope of the resilience assessment and planning.

Table 5.1. Potential Hazards to Resilience

Categories of Hazards	Hazards
Natural, Environmental, Climate Change and Extreme Weather Events	Avalanche
	Drought
	Earthquake
	Erosion
	Extreme Heat
	High Wind
	Increased Precipitation (Rain, Snow, Ice)
	Landslide
	Hurricanes
	Tornados
	Rockfall
	Sea Level Rise
	Storm Surge
	Temperature fluctuation
	Wildfire
Human-Induced	Adverse Actor Physical Threat
	Autonomous Vehicles
	Congestion
	Cyber Attack
	Driver Human Error
	Population Growth
	Toxic/Flammable Substance Exposure

Source: Authors' interpretation

Asset Data

Once the scope of the vulnerability study is known, obtaining information about the assets is the next step in the framework. As FHWA suggests, for roadways, this may be the suite of commonly considered attributes to identify capacities and use of assets as well as geospatial data regarding location in interconnectedness of the network. Having a clear understanding of the entire system under consideration is important for any long-term planning study. From our perspective, knowing how assets interact to form transportation outputs and socio-economic outcomes is important for understanding how the system should be modified in the future. Following our logic model described in Chapter 3, the inputs to the transportation system are not simply the physical assets but also include the human and equipment aspects that can be used in conjunction with the physical infrastructure to alter the impact of disruptions due to shocks and stresses. Incorporating these broader sets of assets is important once we take a resilience focus rather than simply a vulnerability assessment. These other assets may provide alternative strategies for improving the systems resilience to the identified shocks and stresses.

The logic model characterized in Chapter 3 provides a road map for mapping the entire system and not just the physical network. In addition, criticality of each of the assets needs to be identified and the choice of metrics is important to be consistent with both a systems and network perspectives. From our AREA resilience perspective, reducing assets criticality by reducing reliance on individual assets or by reducing the probability that an asset is taken offline increases the resilience of the system. By having alternate routes or modes available or by expanding capacity, any individual asset becomes less critical to the functioning of the system as a whole. This increases the resilience of the entire system to avoid cascading effects that could arise if a critical asset where to be taken off line. As we increase AREA capacities we are less likely to have disruptions while simultaneously reducing the impact of a disruptions on system and avoiding cascading disruptions that can percolate through the transportation system. Additionally, by focusing on the entire asset base, alternative processes for increasing resilience may be realized.

Hazard Data

As discussed in Chapter 3, knowing what assets are exposed to what hazards is important to determine to what shocks and stresses the system is building resilience to. The VAF was developed for planning for climate change impacts. As such the focus is on climate and weather-related events including, for example, flood, drought, sea level rise, and extreme precipitation

events. Although climate and weather-related hazards are important, a wider array of hazards should be considered. In conversations with the stakeholders described in Chapter 2 and Appendix A, transportation planners are increasingly concerned with potential cyber-attacks directly on transportation assets and indirectly on energy production. As such, distinguishing as to whether the hazard is system wide or just on a subset of the assets is important. Understanding the distribution of hazards across the system as there may be approaches to increase the resilience of the system to multiple hazards with minimal additional investment. Knowing how hazards interact with the system may also reveal resilience investment strategies that are tied to reducing exposure rather than increasing the simply hardening assets. In an ideal world, layers of exposure maps in a GIS platform would be available to visualize and analyze alternative investment strategies.

Assessing Vulnerability/Resilience

The VAF outlines three separate approaches to assessing vulnerability: (1) Stakeholder Input; (2) Indicator-Based Desk Review; and (3) Engineering Informed Assessments. The first two of these will be the focus for us as these are system level approaches whereas the engineering informed assessment is at the project level. In addition, more data intensive and modeling approaches could be used but will depend on the capacity of the agency and available skill sets. Given our discussion in Chapter 7, we would advocate for indicator-based desk reviews or modeling approaches.

The stakeholder input assessment is an approach that relies on institutional, subject matter experts to identify and rate potential vulnerabilities. The AREA approach to resilience highlights alternatives ways subject matter experts could approach resilience from a systems-level perspective. Given the subjective nature of the stakeholder input process many of the potential improvements may go unnoticed.

Based on our discussion in Chapter 4, there are a suite of metrics that can be used to assess the resilience of the system incorporating the criticality of the assets as well as the exposure of the assets. The organization of the metrics in Chapter 4 allows a direct translation of the AREA interpretation through the logic model to appropriate metrics that could be considered in a resilience assessment. Developing these metrics at the system and asset levels will allow for greater fidelity of the resilience of the pieces as well as the system. Importantly, these two approaches can be combined as a check on the metrics. Not all aspects of the system can necessarily be easily quantified, and some aspects of the system may fit into the suite of metrics that have been chosen. As such, incorporating institutional knowledge into the assessment can provide further context for assets or sub-systems lacking resilience and alternative approaches to increase the resilience of the system.

The logic model and the AREA interpretation provide high level system mapping and perspective on how the system would respond to the hazards identified in the previous step. Because it may be difficult to assess how assets and, therefore, the system is affected by different

hazards, it may be necessary to develop models that characterize how the chosen metrics respond to disruptions. Especially when considering change in travel to or congestion that are functions of the system capacities, system demands, and potential disruptions, it will be difficult to assess without such models. Importantly though, such models exist and can be calibrated to most networks. These models will highlight subsystems and assets that are more or less resilient to the hazards considered. Additionally, by developing metrics consistent with the AREA interpretation, planners may see alternative solutions that could be considered in the next step. Understanding the transportation network as a whole, including non-infrastructure assets, and taking a systems approach to the analysis will provide a rich set of data to know more about the system. Importantly, know about both the exposure and the consequences that arise due to the criticality of assets once disrupted is key to moving forward. It is not simply exposure or criticality that matter but the combination of them as discussed in Chapter 3.

Identifying, Analyzing, and Prioritizing Options for Increasing Resilience

As discussed previously, using the concepts of criticality and exposure while viewing the system through the AREA interpretation of resilience provides a means to identify alternative strategies to increase the resilience of the system. As discussed in Chapter 4, resilience is a latent construct that is difficult to quantify and analyze as a whole but should be considered through the AREA interpretation so that capacity and equity concerns can be jointly considered, and solutions identified that take into account the different aspects of the AREA interpretation. By taking a systematic approach using the metrics identified in the previous step, solutions or, at least, the approaches may be identified more readily.

Once a suite of potential solutions has been identified, there are several different techniques that can be used to evaluate and prioritize as identified in the VAF. For example, multi-criterion analysis can be used to highlight the tradeoffs across many different dimensions such as environmental impacts, equity impacts, cost, feasibility, and changes in the metrics identified for measuring resilience. How each of the proposed solutions affects the suite of metrics identified allows each of the potential solutions (projects) to be considered on a level playing field so that stakeholders better understand the tradeoffs involved from competing solutions. In addition, co-benefits may be identified that projects provide that are outside of the scope of the transportation system but may be of importance to the larger socio-economic system or other systems in the system-of-systems.

In addition to multi-criterion analysis, there are a suite of different economic analyses that can be used to evaluate solutions. These include but are not limited to economic impact analysis, benefit-cost analysis, and life-cycle cost analysis. More recently there have been efforts to incorporate the ideas of risk and resilience to hazards in an economic framework. For example, Bond *et al.* (2017) developed an approach for estimating the resilience dividend to compare different projects that may have similar targeted outcomes where the resilience dividend is defined as the aggregate difference between two projects one that takes a resilient approach and

the other a traditional damage risk reduction approach (or no project at all). Although the approach has not been applied to a transportation project specifically, the approach is general enough to allow for consideration of transportation projects. Each of these economic approaches has strengths and weaknesses and require different technical skills and capacities that may or may not be present in different organizations.

For example, if an asset is exposed to hazard that makes it vulnerable to closure, there are a number of different alternatives that should be considered rather than simply hardening the asset. The main goal of the transportation network is to move people and freight to where they need or want to go. By only focusing on the absorptive capacity, through hardening, there are dimensions that have not been considered such as increasing the adaptive capacity by either adding alternative routes or alternative route capacity. Additionally, pre-stationing of repair materials near the asset may provide additional restorative capacity. A combination of all of these increases in capacities could provide a more cost-effective approach for increasing the resilience of the entire system and not simply the resilience of the asset. The focus should be a network rather than an asset resilience. Having options across the spectrum of capacities is important given the scarce resources that transportation agencies possess.

From our perspective, the prioritization of options should be considered by the stakeholders and decisionmakers rather than the analysts. As such, we believe that the prioritization aspects should be considered in the next step. That is, the analyst should be identifying the key trade-offs across projects while the decisionmakers should weigh those tradeoffs against each other in terms of the goals and priorities of the organization and the users that it serves.

Incorporating Assessment into Decisionmaking

Incorporating resilience into decisionmaking is a cultural shift for most institutions in that traditionally planners, when confronted with decisionmaking around risk, default to traditional damage risk reduction techniques such as hardening or moving assets. As the Resilience Dividend Valuation Model (Bond *et al.*, 2017) makes clear, the value of using resilience considerations is that the benefits of resilience investments accrue during normal times as well as times of disruption. By taking a more holistic view of the transportation system and the range of assets that are inputs to the system, decisionmakers must incorporate a wider set of considerations than simply the risks that assets face and the impact of disruption.

Resilience assessments should make information about alternative strategies accessible to decisionmakers. Providing the appropriate trades-offs to decision makers is important to understand how investments targeting the AREA concepts, and not just damage risk reduction, can be incorporated into the suite of strategies available to increase the resilience of the entire system. The solutions identified by incorporating the AREA concepts, together with the systems mapping identified in the logic model, and incorporating the dual concepts of criticality and exposure will allow for alternatives that will increase the functionality of the transportation system in normal as well as disrupted operations. The value of incorporating resilience

assessment into decisionmaking is that more cost-effective approaches may be revealed by taking a more holistic approach to infrastructure. The focus should be on the outcomes and not the assets themselves in terms of the movement of people and freight to places that they are needed or wanted.

Although it may seem daunting to incorporate resilience in to the entire assessment and planning process, the existing vulnerability framework can readily be expanded to incorporate the ideas and perspectives of resilience. Using the logic model to map the system and the AREA approach to better understand alternatives should provide an accessible means to incorporating resilience into the planning process via the vulnerability assessment framework already available.

6. Conclusion

Building resilience into the transportation system requires a change in perspective from one of protecting every asset to a systems view. It is not simply the direct transportation infrastructure that is important in building resilience but the human and collaborative relationships that matter in providing a resilient system. By mapping the system through the logic model developed in Chapter 3, it provides a means to characterize the entire system and the goals and outcomes that the system is built to achieve. The AREA approach provides a formal means to better develop the suite of strategies that are available to a planning organization working to build more resilience in their transportation system. Resilience, by its very nature, is difficult to measure; however, recognizing that the AREA capacities are latent constructs, we can use this model to guide our understanding of the nature of resilience and how to improve it from a systems approach. Although a resilient transportation is the ideal, we can only move to improve the resilience of the system as there will always be exposures for which we cannot plan either because they are outside of the planning scope or are at a scale outside the bounds considered. Most importantly, our goal of incorporating additional resilient capacity is to build a better functioning system in normal and disrupted times.

Different planning organizations will have different goals and circumstances. There exists no one size fits all approach that will work for all organizations. Our hope is that by taking an alternative perspective and viewing resilience to shocks and stresses as part of the culture, an improved transportation system will evolve. Matching goals for the transportation system with metrics that evaluate the system will improve the analysis and allow transportation planners the ability to relay the appropriate trade-offs for decision makers. Knowing how alternative projects aim at similar goals achieve those and at what cost will improve decision making by expanding out the suite of available strategies to achieve similar outcomes. How the system is modified is less important than how the system responds under different shocks and stresses. The more information decisionmakers have about alternatives for achieving similar ends can only improve the planning process.

Importantly, existing frameworks and assessment tools need only minor modifications to more fully incorporate the concept of resilience. It is more about the framing of the problem and the perspective that planners take then the process of decision making. Vulnerability assessments can be easily modified to better incorporate the resilience perspective.

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Appendix A. Stakeholder Interviews

RAND interviewed several transportation experts to understand the breadth of challenges and risks that are faced in transportation infrastructure planning and investment as well as the benefits and values to the transportation systems and other social, economic, and environmental systems that result from these plans and investments. The goal of these discussions was to better understand how stakeholders use information on the costs and benefits of resilience when making long-term investments in highway and transportation infrastructure. The interviews also provided insight into how stakeholders think about and understand transportation resilience, which may influence their planning and investment decisions. The information gathered from these interviews was critical to ensure that the outputs of this work are both valuable and implementable to stakeholders. In this chapter, we first describe how we selected our stakeholder sample for interviewing and the types of stakeholders interviewed. We then summarize the information we derived from these discussions, which we used to inform the analytic framework presented later in this report.

Stakeholder Sample and Methods

In a system-of-systems approach to understanding transportation resilience, RAND selected stakeholders who would represent the various types of transportation organizations in the United States, that face similar and different sets of challenges but that are also interconnected in effort, in desired outcomes, or through inter-jurisdictional areas or the transportation infrastructure itself. The stakeholders included organizations directly involved with transportation infrastructure planning and investments through implementation, planning, or policy including MPOs, state DOTs and federal transportation offices and committees. This range of stakeholders allowed RAND to capture an understanding of all levels of transportation planning.

Sampling Methodology

Participant Selection and Recruitment

RAND used convenience and snowball sampling to identify and recruit participants for interviews. These participants were found through A) strategic online searches, B) recommendations from the TRB advisory panel for this study, and C) subject matter experts and practitioners who were contacts of the RAND team.

The online searches included review of several official federal, state, and metropolitan planning organization websites to find relevant stakeholders, such as the staff of a given state's department of transportation whose transportation planning experience included a stated transportation resilience aspect/intent, as well as those for whom resilience was not a stated focus

of their work but their work was closely linked to the topic, for example state DOT emergency relief program staff engaged in disaster response. For the metropolitan planning organizations that were considered, RAND targeted directors of MPOs, planners or team members who run a transportation resilience project or team, and others who worked closely with community partners and other state level agencies and local jurisdictions. Federal level stakeholders were also recruited to provide insight into their work in transportation resilience, as well as an understanding of relevant federal requirements and big systems thinking that influences state level departments of transportation and MPOs. Invitations to participate were emailed; the recruitment e-mail can be found in the next section of this appendix.

Final Sample and Interview Timeline

We conducted a total of nine interviews at eight organizations over three months. We acknowledge this is a limited sample within the entire U.S. transportation network but we sought out a total of nine interviews to fit into our study timeline represented coastal locations as well as those in the interior of the country; international, state, and county borders; both rural and urban areas; and areas with local routes as well as those with major commerce corridors (highway infrastructure) such as I-10, I-70, I-80. While we tried to draw as geographically representative a sample as possible, out of the 13 organizations invited to participate we encountered non-response from 2 MPOs and one state DOT. 4 , and Also, one state DOT declined to participate. This resulted in an 62% response rate for organizations contacted. Table A.1 lists the organizational levels and locations of participants:

Table A.1 Transportation Stakeholder Locations

Level	Location	Total Organizations Interviewed
Federal	Washington, D.C.	2
State	Colorado, Iowa	2
Metropolitan Planning Organization	Florida, Louisiana, Tennessee, Texas	4

Source: RAND.

Interview Protocol

The interview questions were based on a semi-structured protocol, and tailored to diverse participants. For example, we asked federal representatives what the major disruptions to the transportation system and infrastructure are generally and if they had any examples, but in speaking with an MPO representative, what the disruptions are specific to their area. The full interview protocol appears in the end of this appendix The discussion included questions that

were intended to at a base level; a) capture the current connectivity between transportation planning organizations, connectivity with organizations in other sectors (health, education etc.), transportation system benefits, costs, and challenges as well as current implementation and plans for dealing with shocks to the system. All of this information was discussed understand current transportation system resilience considerations by transportation planners and policymakers, and what is needed in the future to ensure a more resilient transportation system. The discussion items were directly tied to the development of the conceptual framework in parallel with the review of literature on transportation resilience. Generally, the questions asked about the stakeholders' roles, who they interact with for transportation planning and investment, their priorities, the costs and challenges they consider as well as the benefits, how they use the information they have to inform long-range planning and investments in highway and transportation infrastructure, and their perspective on what is needed for the system to become resilient or maintain resilience. Interview discussions were captured through notetaking. Data from the notes were then reviewed in aggregate to identify topics that came up in more than one conversation as well as detailed examples of problems, successes or recommendations related to planning for transportation resilience.

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What Stakeholders are Saying about Transportation Planning and Resilience

In this section, we discuss a summary of the information provided by stakeholders in order of the questions asked in the protocol. These questions covered things like who organizations work with in transportation planning and investment, their main priorities and the challenges to transportation planning as well as the benefits provided by the transportation system. We also describe how stakeholders think about and define transportation resilience; what they see as the benefits and value added of a resilient transportation system; how they measure—or would measure—these benefits; and their perspectives on the main factors contributing to transportation resilience. We acknowledge that the topics discussed may not be reflective of all entities in the transportation network. Topics discussed by stakeholders are presented here. This information is linked to the conceptual framework we discuss in chapter 3.

Organizations Working in Transportation Planning and Investment

The network of organizations involved in transportation planning and investment for transportation infrastructure is broad and diverse. This breadth and diversity are especially important to understanding the system-of-systems framing of the transportation system, because transportation networks needs and challenges are diverse with varying priorities. We provide the following examples to illustrate the breadth and scope of the transportation planning network. However, at the same time, we acknowledge that the depth and type of interaction between MPOs, state departments of transportation and the diverse organizations and sectors varies widely.

The *MPOs* we interviewed highlighted that day-to-day interactions with transportation-focused entities for transportation planning purposes can include the county or counties in their jurisdiction, neighboring counties, member jurisdictions, and local and city governments. Also, some MPOs interact with other departments or offices in their host agency, and some interact with the state for policy matters, for preparation of their Transportation Improvement Program (TIP),[13] or financial planning. The following description from one MPO illustrates the variety of interactions:

> "[We] interact with different groups in the district office of DOT [about] everything from preliminary project scoping and programming decisions and modeling to [talking with] design folks, and operational folks working on safety issues."

The entities with whom MPOs interact may depend on who owns various assets of the infrastructure. For example, in Texas, some bridges and roads are owned by the state, resulting in considerable interface between the state DOTs and MPOs who may access databases that track the current status of roads, their maintenance, and future construction. MPOs may also interact with multiple state departments of transportation if, for example, the MPO crosses state lines. Other entities with whom MPOs interact for transportation planning and investment efforts include regional planning commissions, for issues such as air quality and economic development; port authorities; and transit authorities (e.g. Memphis Area Transit Authority (MATA). Others mentioned advocacy organizations such as AARP or those organizations focused on pedestrian biking and airports.

In addition to working with what are considered traditional transportation related organizations or entities, MPOs also work with other sectors to achieve their goals. Examples include local public works departments and school districts and boards for planning efforts such as safety in transportation, or the proximity of a new school location to transportation corridors. Other sectors that MPOs work with include local small businesses, other businesses for economic development, medical districts, hospitals, public health departments' divisions for water and air quality, commissions that reach out to constituent groups (e.g., groups that represent individuals with disabilities), other offices working on broader resilience issues, and, law enforcement for safety initiatives. One MPO stated:

> "An example of law enforcement interaction would be—with a land use agency for planning a community [development in a certain location]—there is interface with the community. Programs that talk about how to do planning to improve safety (lighting, building placement, glass structures)—when we work on those, law enforcement comes in at the same time."

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[13] A Transportation Improvement Program is a federal requirement for all MPOs, which must develop and maintain a multi-year plan for all transportation projects that receive federal funding. More information can be found at: https://www.transit.dot.gov/regulations-and-guidance/transportation-planning/transportation-improvement-program-tip.

The *state level stakeholders* we interviewed mentioned one example of interaction with a local affairs office:

> "Its mission is to look at resiliency cross-sector; housing, healthcare, transportation, water resources, health and environment, natural resources."

More generally, other state level stakeholders noted they interact with FHWA and many other organizations, especially after a crisis such as a disaster situation. This can include interaction with the management department of the Department of Homeland Security to connect local agencies and resources, the department of natural resources for debris disposal, the National Guard, the department of revenue, and cities and counties. One federal committee whose responsibilities are related to transportation resilience includes members from all state departments of transportation, with members representing diverse areas of expertise including emergency specialists, planners, engineers and policymakers to deal with resilience issues and other related topics such as construction and security. This diverse membership provides a more comprehensive view of transportation needs and considerations for resilience.

Finally, stakeholders noted a few additional key influencers in transportation planning and investment with whom they might not interact with at all or regularly or might interact with only tangentially. This list includes organizations like certain local or grassroots advocacy groups, national institutes such as the National Institute of Standards (NIST), other offices of state government such as the office of tourism or the office of development, some divisions of public health and environment, those working in freight, and those working and making decisions on land use. The stakeholders emphasized the importance of including as many sectors and influencers as possible in the transportation planning and investment process.

> "We couldn't think of anyone we knew of that we don't interact with. If we know about them, we try to divide up our staff to be a part of, for instance, the Chamber of Commerce meetings or local major road committees."

Others emphasized the importance of breaking down silos across different organizations or entities in multiple sectors that engage in transportation planning and investment.

Communication about Transportation Resilience

The level and detail of communication about transportation resilience varied among the stakeholders interviewed and the entities they work with in transportation planning and investment. It became evident that in some locations, the conversation about resilience has been ongoing and it is a well-known concept. For example:

> "[We are] talking to several agencies about opportunities to include hardening treatments in some projects they had underway."

> "Everybody we interact with is familiar with that term. It comes up within our goals and objectives adopted within our long-range plan, so it's heard by all multi-modal initiatives, and the state DOT. Not just the engineers but the mayors."

However, in other locations, the level of investment in resilience discussions at the time of these interviews was more nascent, and stakeholders were continuing to seek buy-in. One MPO noted they were starting to inventory all of their resilience work and reaching out to their local planning departments, engineers, and flood plan managers to expand the conversation. A few others noted small efforts to initiate this type of communication during meetings; that such efforts may not yet be well coordinated; that more effort is needed for better coordination; and that some of these discussions depend on government acknowledgement and priorities at the state level, which also raises the issue of funding resilience efforts. Some interviewees noted that the concept of resilience is not yet understood or agreed upon by different levels of government and some perceived lack of interest at the state DOT level . Also mentioned was the importance of sharing information such as after-action reports from the state following major events, in a timely manner, with MPOs of all locations flooded by hurricanes to help plan for future stresses and shocks.

In terms of interaction and communication with other sectors, one stakeholder noted that a representative of a transportation sector cannot affect private sector building development code or plans because the developers are not currently engaged in the transportation conversations. This is a factor to consider in effective transportation resilience if for example building construction influences transportation infrastructure quality related to drainage or impermeable surfaces.

Transportation Infrastructure and Investment Priorities

Many stakeholders discussed their transportation planning and investment priorities in terms of their long-range transportation plans (LRTP): according to the U.S. Department of Transportation, LRTPs typically cover at least a 20-year timeframe and describe the vision and ways to achieve the vision.[14] CFR 23 § 135 directs states to consider certain issues as part of their statewide transportation planning process. During interviews, some MPOs' stated priorities that include the following:

- preserving and maintaining existing infrastructure
- updating public transportation
- reducing crash vulnerability, and
- reducing congestion through roadway expansion, an increased number of thruways, and traffic management.

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[14] "FHWA/FTA Transportation. Planning Capacity Building Program," *Metropolitan Transportation Planning: Executive Seminar*. As of February 19, 2019. https://www.planning.dot.gov/Documents/MetroPlanning/metroTrans.htm

MPOs also stated their desire to ensure a safe system; enhance transportation options to include not only vehicles but also modes like bus service, greenways, and bike/pedestrian infrastructure; and more equity by providing more access to any mode to travelers in a given area to get to jobs. A review of other MPOs' public websites identified some additional goals such as environmental protection; public participation; enhanced connectivity and integration; positive health impacts; economic vitality; and responsible, well-allocated funds.[15]

States emphasized priorities such as safety, mobility with resilience incorporated, economic vitality, and resilience as the criteria for long term investments such as national highway freight program. Following an event, priorities they emphasized were the safety of human lives, followed by restoration of property and getting back to business as usual, and sharing information on lessons learned with transportation planning and design experts.

Federal stakeholders also emphasized the need to determine the proper courses of action for dealing with the flooding that is resulting from increasing numbers of weather events and sea level rise. The options they mentioned included simply rebuilding, rebuilding differently, or moving the infrastructure. To determine how to make the transportation system more resilient to such stresses and how to make such considerations a regular part of planning and design, it will be important to understand the implications of those options in a broader, long-term context.

Transportation Funding

With the exception of pilot projects that have been funded by FHWA (USDOT, 2018), none of the interviewees mentioned any universal funding streams for projects or system level work specifically related to achieving transportation resilience. One interviewee mentioned state level interest in funds being compartmentalized for proactive investments. MPOs noted that funding is federal, such as that provided through formula funds from FHWA for surface transportation and other federal grants with local matching. However, MPOs also mentioned state funding for planning for disadvantaged communities, state bonds, fuel taxes, property taxes, and toll revenues. Other MPOs said that they are starting to receive more local dollars from conservancies, individual donors, and developer impact fees. Some stated that achieving adequate levels of funding for transportation can be difficult, and one noted funding for nationwide infrastructure is not enough of a government priority:

> "One of our biggest challenges is funding at the state level. Our gas tax hasn't changed since the early 1990s. Legislature attempted to raise it last year and failed and we don't anticipate it being raised in near future. It's gotten to the point where the state will no longer have enough funds to make a 20% match on major projects."

[15] This list contains a summary of information found on the websites for the following metropolitan planning organizations: Abilene, TX, Adams County, PA, Central Massachusetts, and Michiana Area Council of Governments, Indiana.

In emergencies, relief funds come from federal sources such as FEMAor FHWA (USDOT, "Emergency Relief", undated), but interviewees noted that the processes for applying and receiving funds can be difficult. One stakeholder described a situation where the thresholds and criteria to receive state level emergency funding were understood, but the amount of emergency funding available was lower than needed. It was also noted that reimbursement for costs incurred in an emergency can be limited. Thus, while transportation organizations are obligated to maintain transportation system safety after an emergency, the source for the necessary funds to do so may be unclear.

The Benefits Resulting from the Transportation System

The importance of the transportation system infrastructure and services as it contributes to benefits to the transportation system and other social, economic, or environmental systems was highlighted by stakeholders, who provided several examples.

Transportation provides a system for people to move around different regions. And as one person noted, the system is also:

> "the conduit/artery of the community that ferries people to work, recreation, daycare, senior centers. You can't get anything done in the community if [the] system isn't functioning properly."

Transportation planning and infrastructure influences the location of housing facilities, utilities, and other elements of the built environment in the transportation network, e.g., their proximity to major roads or routes as well as green infrastructure which can improve public health. Transportation planning also influences economic development in that it enables movement of people and goods around a region and creates access to employment..

Transportation Challenges

MPOs and state DOTs noted challenges that can be roughly divided into three categories: disruptions and risks, (challenges associated with) planning and implementation, and future challenges that will have to be accounted for in transportation resilience planning.

Disruptions and Risks

- Extreme weather events, e.g., extreme heat and hurricanes or winter storms that result in downed buildings, flooding, storm surge, Flooding was the most frequently mentioned of any source of disruption and risk from weather events
- Other physical threats such as rockfall, wildfire, land loss and erosion, sea level rise, or dangerous destruction of industry infrastructure such as an oil refinery resulting in a leak or explosion
- Infrastructure outages such as loss of roads and bridges, which have economic impacts when they result in loss of access to jobs
- Cybersecurity threats from adversaries with intent to destroy transportation infrastructure

- Population growth

Planning and Implementation

- Lack of all hazards planning and back up plans, e.g., a freeze that occurs in an area that does not usually experience such events and lacks the resources to deal with them (e.g., salt trucks). Or in the case of a shock or stress due to an emergency, failure to formulate plans to evacuate people who lack access to a personal mode of transportation or public transportation and no back up plan if those systems have also been disrupted
- Congestion
- Underdeveloped public transit systems that necessitate reliance on private vehicles
- Construction and the timing of that construction on major roads and routes
- Limited funding and few alternate routes and limited infrastructure maintenance (e.g. paving potholes after winter events)
- Limited availability or usefulness of data for decisionmaking for current or future predictions of extreme weather
- Lack of political support—or difficulty in prioritizing funding—for transportation planning
- Conflict between state, county, and city government priorities that have local impacts
- Change in transportation planning management with slow adoption of new practices
- Increased costs for labor and scarce resource materials, sometimes due to changing U.S. tariffs
- Jurisdictional overlap, lack of clarity over who owns certain road infrastructure and who can—or understands the need to—act, or work together to address issues that affect multiple jurisdictions
- Unclear roles and responsibilities, workforce shortages. .

Future Challenges

Stakeholders suggested that in addition to current challenges that may be exacerbated over time, they will face a number of new challenges in transportation infrastructure planning and investment that will arise within the next five to ten years. This list includes both those challenges currently faced they think will be exacerbated in addition to future challenges not yet mentioned.

- Population growth, increased “mega-regions,” and resulting increased congestion
- Increased costs for which funds may not be available
- Policymaker support
- Coordination of long range and immediate planning with a shift in mindset to understand how a 20-year long-term plan can be more useful than a short-term plan in an emergency, and clarification of what constitutes urgent issues (e.g., storms)

- Autonomous vehicle adaptation and service including fueling stations and resulting cyber issues

- Climate change impacts and symptoms
- Greater challenges with hydrology modeling and planning with increased amounts of impermeable surfaces
- Increased freight traffic that results in increased wear and tear in infrastructure such as roads and bridges
- Increased need for maintenance and preservation

Transportation Resilience

Definitions of Transportation Resilience

Although most MPOs we interviewed had no official definitions of transportation resilience in their organizations, some mentioned guidance from Federal and State levels that informed their understanding of the term. This guidance included the FAST Act and Executive Order 5520, which focuses specifically on transportation resilience related to climate change and extreme weather events (USDOT, 2015; USDOT, 2014). One federal stakeholder noted that DOTs are currently trying to develop guidance on integration of resilience into the transportation planning process, and one state DOT had codified the definition as law. Several interviewees noted that to be useful, the definition of transportation resilience needs to be tailored, narrow, tangible, and then possibly expanded for the future.

The definition of transportation resilience that emerged from our stakeholder interviews can be summarized as follows: the ability to adapt, recover, and respond to—and bounce back quickly from— threats to physical infrastructure and operations, threats to cybersecurity, terrorism, and all hazards; and the ability to minimize impact and ensure the transportation system is still usable (following a shock or stressor).

Several stakeholders mentioned the importance of considering other sectors in their work to understand how transportation can impact the resilience of bigger systems as well as entire regions. Finally, one stakeholder stated transportation resilience as the ability to learn from past experiences to understand how to better respond with what assets you have moving forward as the definition.

Resilient to What?

We asked MPOs and state DOTs to articulate what factors the transportation infrastructure most needs to be resilient to, to address challenges within transportation infrastructure planning and investment. The issues they mentioned focused mainly on climate change and extreme weather events, but also included the impacts of factors such as security and planning. A few emphasized the importance of comprehensive, system level resilience.

Most items that can be considered hazards relate to the challenges noted earlier that stakeholders face. For climate change and extreme weather events, resilience to flooding was the most commonly mentioned need. Other concerns included hurricanes and the accompanying high-level winds and flooding, sea level rise, storm surge, inland flooding, increased temperatures, and severe winter weather. Concerns about flooding were emphasized not just because of climate change but also because of flooding due to building development with poor land use planning. Interviewees noted that resilience in communities and for vulnerable populations requires a reduction of secondary impacts of the transportation system on outcomes such as community health. For example, community health may be affected in a disaster if transportation infrastructure is not operating, and people are stranded without access to exit routes, and there is a lack of potable water. The potential interstate or nationwide impacts of events and were also mentioned; for example, in any event that may result in a shutdown of movement of freight, there is a potential stress or shock to the economic system.

Some stakeholders also mentioned concerns regarding maintenance of physical security. Specific issues they raised included vehicle ramming attacks and threats to cybersecurity. One stakeholder summarized what the others also mentioned:

> "I want to be resilient to everything that could possibly happen – look at what's occurring and say we can either correct this, build our way out of it, or resolve it."

Transportation Resilience Benefits and How to Measure Them

The benefits that transportation resilience could bring to systems were discussed mainly in terms of economic benefits by many stakeholders. They noted that resilience could lead to uninterrupted movement of goods and people, resulting in improved access for businesses to the workforce and goods they need. Infrastructure that withstands disruptions, reduces replacement costs, resulting in long term cost savings. Increasing the efficiency and mobility of infrastructure by increasing transportation options improves connectivity. Some stakeholders also emphasized that increased resilience would increase the safety and future viability of residential neighborhoods. Increased communication and improved warning systems with the public would also provide them with the ability to make more informed decisions about what to do in certain events.

Data and Measurement

The stakeholders we interviewed were not collecting data or using any metrics with the sole intent of assessing or achieving transportation resilience at a systems level. However, this lack of data collection for the express purpose of assessing resilience does not mean stakeholders are not thinking about measuring resilience. Rather, it was clear that some are using primary or secondary data to allow for more resilient planning and investment efforts for certain infrastructure. Examples of metrics or data they mentioned using included: crash data from DOTs, information on community participation in transportation, inventories of assets, and

information on costs and types of damage, road closure time, hours of delay, the use of cost-benefit ratios generally, extended life of certain infrastructure like bridges, repair costs in emergency situations, and congestion. One interviewee stated that congestion can be an indicator of a good economy rather than evidence of failure in resilience.

Stakeholders also mentioned a number of other items they are considering measuring to assess resilience. These included: the benefits of emergency relief, avoided disruptions, lives saved, environmental costs incorporated into economic analysis, quantification of impacts of infrastructure improvements on safety, treatment of runoff water, changes in air quality with travel fluctuations, societal resilience to congestion, and decreased mobility. Other considerations were how long emergency services—such as shelters —need to be set up, system vulnerability, portions of roads flooded on an annual basis, frequency of maintenance required for certain sections of infrastructure as well as the costs, economic value of goods/freight to understand economic impacts during disruption, and aggregate review and identification of past design and construction projects to guide future efforts.

Some stakeholders mentioned the potential utility of data that indicate the parts of a system that are still functioning and how quickly the system can recover and become operational again. Several of the stakeholders mentioned that making data available across sectors is important. For example, if ports or the freight industry collect data of potential use to MPOs, a central, accessible data repository for both types of consumers of the information would be beneficial.

Factors Contributing to Transportation Resilience

Stakeholders cited a variety of factors they believed contribute to resilience in transportation infrastructure and the transportation system:

- The need to create a source of funding specific to that goal and to inform practitioners and planners about such funding.
- The need to develop and implement resilience strategies for the short, medium, and long-term.
- The need for an understanding of the connectivity, between transportation programs and systems during events so that appropriate plans result in sustained movement of people and goods.
- The need for more data collection and data sharing about things like floods, to use in local mitigation planning and to predict challenges
- The need to consider not only big, long-term risks but also small day-to-day risks, and to be able to communicate both of those to decisionmakers.
- The need to create better public address systems to communicate information such as evacuation routes during disasters.
- The need to build redundancy into the infrastructure, or “the existence of numerous optional routes/means of transport between origins and destinations that can result in

less serious consequences in case of a disturbance in some part of the system" which might include access to additional bridges, crossings, and routes (Xu *et al.*, 2015).

- Efficiency and designs that allow for less deterioration over time or ease of repair and maintenance;
- An understanding of critical assets and the costs when they are down due to an event, including secondary impacts of disruption of those assets, such as the impact of disrupted access to jobs on the economy.
- Planning that incorporates infrastructure alternatives such as roadway elevation; newer, more permeable, road materials; drainage or retention services; informed by information such as hydraulics assessment and inundation flow mapping for flood control.

As one stakeholder said:

> "If you don't consider what you have and what you end up with, don't think you can be resilient."

And another stated:

> "Knowledge and data – resilience is all about being proactive – an event has already happened and you can repair and recover but you can't prevent it anymore – so having the data and knowledge of where things are and what we need when we needed it – incorporating that resilience into decision making process would let us not just improve mobility but also resilience, and that just comes from knowledge and information."

Other Important Considerations and Suggestions

When asked about any other considerations for transportation resilience, stakeholders had a number of suggestions.

- Stakeholders enunciated a strong desire for more work in transportation resilience and suggested a need to create a culture shift that would make resilience efforts a national initiative, with consideration of current investments and future risks.
- They clearly expressed the need to inform other stakeholders in transportation and other sectors about what transportation resilience is, why it is important for planning, and the potential impacts on systems.
- The recommendations of stakeholders for policymakers include increasing federal standards and guidelines pertaining to transportation resilience, and improving opportunities for MPOs to consult each other for guidance on how to meet those standards. The stakeholders suggested further that the standards should extend beyond transportation agencies in their applicability and should be crafted to target each of the relevant audiences. They emphasized the importance of communications across disciplines, getting other stakeholders, such as engineers, to understand and engage in resilience planning and appropriating dedicated funding for transportation resilience efforts.

When asked about the practicality and benefit of federal and state requirements related to transportation resilience and planning, many stakeholders cited the FAST Act, MAP-21, 23 C.F.R. § 667 final rule, and Executive Order 5520, and the National Environmental Policy Act (NEPA). In general, stakeholders welcomed these policies, and some expressed the belief that that the policies stimulate motivation and interest in the resiliency space for those states not already working in it. However, some stakeholders found inconsistency with how regulatory requirements for addressing resilience were understood and handled at the state and MPO level, and noted that currently, only a handful of states have specific requirements.

A number of suggestions both broad and detailed were aimed at the needs of practitioners:

- A decision tool and criteria to incorporate resilience into transportation
- The need to break down silos so that experts with different industry and community perspectives, such as hydrologists, flood plain managers, and railroad and port representatives, can work together
- The need for individuals, regions, and governments to recognize issues associated with climate change and move to the next step of taking action.

Finally, some suggestions related to implementation:

- The need for better design processes, for example the need to better design work zones for major construction to ensure drivers can traverse these sites safely and smoothly
- The need for better provision of information to drivers or passengers of public transportation on construction plans and timing
- Application of the “build better” concept, for example in system wide drainage improvements and raised roads .
- The need to review the congestion management process and shifting the way people travel, including factors like the quality of signs, paint markings, and other tools for driver communication.

Implementation of these suggestions would require funding and shifts in mindset. Overall some stakeholders noted the importance of considering how transportation systems and infrastructure, as well as the communities they impact, can recover, absorb shocks, and manage disruptions efficiently.

Interview Recruitment and Protocol

Recruitment E-mail

Dear [participant name],

Hello, my name is [RAND team member name and role] at the RAND Corporation (www.rand.org). I am conducting a study on behalf of the Transportation Research Board (TRB) to help them develop an analytic framework for the Federal Highway Administration (FHWA) to be used for vulnerability assessment.

Are you willing to participate in a phone discussion with me on this topic as an important decisionmaker and professional in the field of transportation planning?

We believe you can provide a valuable perspective for the development of our analytic framework. We would like to understand what the expected needs for disruptions and risks are to resilience in the transportation system to help maintain long-term economic transportation resilience.

This discussion would be scheduled at an agreeable time for you, and is expected to last about one hour, will not be recorded and will be confidential, but we would like to take notes for our analysis. These notes will not be shared outside of the research team. We realize your time is valuable, and we truly appreciate your contribution to this research.

If you are willing to participate, please contact me, [e-mail address] to set up a time to talk by **[Month, Day]** if possible, we can schedule for another week more agreeable for you within the 9-5 pm EDT time zone**.** If you have any questions, please feel free to contact me or the project Principal Investigator [Principal Investigator name and email]. This project has been approved by RAND's Human Subjects Protection Committee [study number]. Thank you for considering and we hope to hear from you!

Sincerely,

[Signature Block]

Interview Protocol

Informed Consent

RAND is working in consultation with the Transportation Research Board to develop an analytic framework for incorporating resilience into the Federal Highway Administrations' Framework for Vulnerability Assessment. Today's discussion will focus on how your organization develops long-term investment priorities and the role of uncertainty, risk, and resilience in the decisionmaking process. The discussion of our meeting will be kept confidential. RAND staff will be taking notes during the meeting but only summary information from the meeting will be included in our final report. We will not identify a specific individual by name or affiliation without his or her permission.

Although documents related to this project may reveal what types of organizations participated in these interviews, your responses and ideas will be reported only in the aggregate. Your individual responses will not be reported publicly and neither you nor your organization will be identified in public reports. Your participation in this interview is entirely voluntary. You do not have to participate in the interview and if you participate, you should feel free to skip any questions. We believe the risks to participation are minimal.

Do you have any questions about our confidentiality procedures before we begin? [If yes, respond to all questions. If no, proceed with discussion.]

General Background Questions

1. Can you describe your role at [add respondent organization here] and how long you have been working there? Would you say your work falls into the; policy, financial, or technical side of transportation planning?

2. What transportation organizations or entities do you interact with? Such as the [Choose appropriate based on Q1 answer- city, district, county transportation officials from State Dept. of Transportation, Metropolitan Planning Organizations, Public Transportation Organizations of FHWA or FTA]?

3. What other systems, sectors, or entities do you interact with on a regular basis when dealing with transportation planning and investment? [Probe: These could be systems including neighboring governments and jurisdictions, hospital systems, educational systems and private sector companies, police departments, etc.]

3A. Are there other systems, sectors or entities you do NOT interact with, but you think influence transportation planning and investment? (E.g. city councils.)

Long-Term Investments in Transportation Questions

[Introduction] In these next few questions we are trying to understand how you use information on costs and benefits to inform long-term planning and investments in highway and transportation infrastructure and what is needed for the system to become resilient or maintain resilience.

4. What are your main priorities transportation planning and long-term investments?

5. What are the main sources of funding for transportation investments and what are the uncertainties associated with that funding?

Issues/ Risks/ Challenges

6. What are the major disruptions to the transportation system and infrastructure in your area? By disruptions, we are referring to congestion, pot holes, problems with the physical aspects.

7. What are the major risks to the highway and transportation infrastructure including flooding, erosion, rock fall, snow, or other natural occurring phenomena? Which of these risks to you plan for?

8. What are the major challenges that your organization face in terms of highway and transportation planning? This includes things like: funding, jurisdictional overlap, tradeoffs in terms of location of activity.

9. What are the major issues that arise during planned implementation efforts or projects such as unreliable contractors, supply of material inputs, available labor, etc.?

10. Do you anticipate any new challenges for planning and infrastructure in the next 5- 10 years?

Transportation Resilience

11. How would you or your organization define transportation resilience? [Probe: Explain this if they do not understand or based on their answer] Generally speaking, we define transportation resilience as: the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions, along with a reduction in overall vulnerability.

Based on that [if not already answered]

12. What do you want to be resilient too?

13. From your perspective, what is the benefit of incorporating resilience into transportation planning? [Probe: Benefits to transportations and benefits to other sectors.]

13A. Are there federal or state requirements related to transportation resilience that you follow? Do you find them useful or challenging?

Benefits

14. What do you see as the major benefits of the transportation infrastructure in your area? Who are they for (who benefits) and what are the types of benefits?

15. Do you to track these benefits/values with data? Does this include certain performance measures? If so what are they? Is any of this data available on your website? [E.g. do you track the impact of transportation disruptions, safety, or operation and maintenance costs?]

16. Of the systems and sectors you mentioned that you communicate with on a regular basis; do you communicate about transportation resilience or is this something new?

17. [If not answered above] Do you have any examples of projects or investments that you have implemented or adapted in pursuit of transportation resilience? [E.g. TIP or STIP]

18. Now that we have discussed transportation resilience in detail, what would you recommend as the main factors that contribute to resilience in transportation planning and investment in your area?

Closing Questions

19. Based on this discussion, is there anything else you would like to add? Anything else we should consider when developing the analytic framing for transportation resilience and long-term planning?

20. Is there anyone else you would recommend we talk to inform our study?

Appendix B. Literature Review on Resilience

The concept of resilience is gaining ground in research communities that study hazards and risks as a means of moving beyond traditional assessments of risk and vulnerability. While the frameworks and analytic methods for traditional risk assessment are fairly mature, this is not necessarily the case for resiliency. There have been a few systematic efforts to assess the most effective strategies to build community resilience (National Academies, 2012; Acosta, Chandra, and Madrigano, 2017). One of the main obstacles to identifying effective strategies is the lack of an agreed upon definition of resilience and a common framework for assessing and operationalizing it. This chapter describes major components of the resilience concept and discusses past resilience definitions and frameworks that appear in the literature.[16]

Approach to the Literature Review

Our overall approach for each of the literature reviews was to develop a library of resources based on searches using widely available on-line data bases and keywords relevant to each of the topic areas. We used Google Scholar and Web of Science using the keywords: "resilience," "resilience framework," "resilience conceptual," "resilience indicators," "resilience metrics," "resilience definitions," and combinations of these terms. Additionally, a database of literature developed at RAND on community response to climate change was used. These two resources yielded a total of 1318 articles. From these, we reviewed the abstracts to look for the words "literature review" or "meta-analysis" to identify relevant literature reviews for three topics, (1) definition of resilience, (2) conceptual frameworks for resilience and (3) indicator systems for resilience. For each of these topics a previous literature review was identified. From these previous literature reviews, we expanded the library of articles to include forward searches of material that cited the literature review using Google Scholar and Web of Science to identify additional updates to the literature. In total, approximately 65 sources were used to develop the literature review.

For the definition of resilience, we built on the review that is contained within Norris *et al.* (2008). Our working definition is in line with the National Academy of Sciences definition that appears in *Disaster Resilience: A National Imperative* as this is the definition currently adopted by DHS. The broad overview of the resilience frameworks in the system-of-systems literature draws on da Silva and Morera (2014) and NIST (2015) as starting points but we also considered over 100 other papers to assess alternatives to the frameworks considered in da Silva and Morera. Our intent is to provide an overview of frameworks that could be used in a decision support

[16] The majority of the information in this chapter has been presented by the authors in past publications but is included again here because the information is fundamental to the framing of this work.

context and not provide an exhaustive list of frameworks. The indicator systems are reviewed in Cutter (2016) with a focus on systems that have been implemented. We include a larger discussion of indices of interdependencies not present in the Cutter review that are directly related to the interdependencies that resilience is meant to capture. These indices of interdependency provide a link between the frameworks considered and indicator systems that have been used by providing a metric for how inter-related the components of the system are.

Conceptual Foundations of Resilience

The concept of resilience has its foundations in materials science, mathematics, and physics, with the focus primarily on equilibrium analysis (Bodin and Winman, 2004). Two main considerations within this realm are the magnitude of a stressor, as measured by the movement of the system from one equilibrium state to another, and the length of time it takes for the system to rebalance once the stressor has been removed. C.S. Holling (1973) was the first to transfer these ideas from the physical sciences to the biological sciences. The distinction between the concept of resilience in the physical sciences and that of the biological sciences, according to Holling, is that in biological systems, resilience and stability are clearly distinct. For example, although an ecological system may fluctuate or have cycles and not be stable, it may be resilient to outside stressors. Holling's view suggests that the main concern of resilience is with how large a stress the system can take and still maintain its integrity, as opposed to movement to a new equilibrium point.

Norris and colleagues (2008) provide a broad overview of resilience definitions that have transitioned from the physical and biological sciences to the social sciences, and Table 3.1 lists these definitions, which come from a variety of disciplines and perspectives. The main commonalities among all of the community-level definitions of resilience are threefold.

- *Absorption capacity:* How large a disaster/stress can a community absorb/resist and still function in the pre-event mindset? Some authors have also described this concept as resistance capacity.
- *Adaptive capacity:* How adaptive is the system to stresses while still maintaining function? This concept can be viewed as the redundancies within the system that enable the system to continue to function (although potentially at a reduced capacity).
- *Restorative capacity:* What is the ability of the system to be restored to "normal" functioning once productive capacity has been reduced, understanding that "normal" may look different after the event than before it.

The ideas underlying the study of resilience are linked to other efforts that emphasize vulnerability and adaptive capacity and by a common goal of reducing the risk to a community from external forces (Lei *et al.* 2014). As Miller et al. (2010), and other authors have noted, resilience and vulnerability should be viewed as complementing each other rather than being at odds. The main distinguishing characteristic between these two views seems to be that the concept of vulnerability focuses on the system whereas the concept of resilience focuses on the

actors within the system; i.e., only the actors can perform actions that increase system resilience and reduce system vulnerability. Likewise, Cutter et al. (2008) note that the shift in focus from vulnerability to resilience among federal agencies may be considered a move toward a "more proactive and positive expression of community engagement with natural hazards reduction."

Beatley (2012) also distinguishes resilience from mitigation. According to this view, resilience focuses on increasing adaptation and learning as well as building underlying capacity to deal with future stressors, whereas mitigation efforts are limited to minimizing and repairing damage (recovery) after the fact.

Components of Resilience

There is a growing convergence of the definitions of resilience used in disaster and risk planning and mitigation that centers on the three principal components of absorption, adaptation, and restoration. These three components are very much in tune with the three phases of disaster planning: preparedness and mitigation, response, and recovery. Although a large segment of the literature still distinguishes between hazard mitigation and resilience development, these two concepts should be considered complements. Distinguishing between hazard mitigation and the recovery process, as many authors have done, may eliminate some potentially beneficial responses to risk. In particular, if the focus is solely on what happens after a disaster occurs, pre-emptive strategies or actions to reduce vulnerabilities (or actions to reduce vulnerability to future events) might be undervalued or ignored entirely. Alternatively, if the focus is solely on hazard mitigation, capacities that are important to the recovery process may be ignored. A less vulnerable community is a more resilient community since it faces fewer disasters from which to recover.

Table B.1. Sample Definitions of Resilience at Different Levels of Analysis

Citation first author, year	Level of analysis	Definition
Gordon, 1978	Physical	The ability to store strain energy and deflect elastically under a load without breaking or being deformed
Bodin, 2004	Physical	The speed with which a system returns to equilibrium after displacement, irrespective of how many oscillations are required
Holling, 1973	Ecological system	The persistence of relationships within a system; a measure of the ability of systems to absorb changes of state variables, driving variables, and parameters, and still persist
Waller, 2001	Ecological system	Positive adaptation in response to adversity; it is not the absence of vulnerability, not an inherent characteristic, and not static
Klein, 2003	Ecological system	The ability of a system that has undergone stress to recover and return to its original state; more precisely (i) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction and (ii) the degree to which the system is capable of self-organization (see also Carpenter et al. 2001)
Longstaff, 2005	Ecological system	The ability by an individual, group, or organization to continue its existence (or remain more or less stable) in the face of some sort of surprise…Resilience is found in systems that are highly adaptable (not locked into specific strategies) and have diverse resources
Resilience Alliance, 2006	Ecological system	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks—and therefore the same identity (Retrieved 10/16/2006 from http://www.resalliance.org/564.php)
Adger, 2000	Social	The ability of communities to withstand external shocks to their social infrastructure
Bruneau, 2003	Social	The ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes
Godschalk, 2003	City	A sustainable network of physical systems and human communities, capable of managing extreme events; during disaster, both must be able to survive and function under extreme stress
Brown, 1996	Community	The ability to recover from or adjust easily to misfortune or sustained life stress
Sonn, 1998	Community	The process through which mediating structures (schools, peer groups, family) and activity settings moderate the impact of oppressive systems
Paton, 2000	Community	The capability to bounce back and to use physical and economic resources effectively to aid recovery following exposure to hazards
Ganor, 2003	Community	The ability of individuals and communities to deal with a state of continuous, long term stress; the ability to find unknown inner strengths and resources in order to cope effectively; the measure of adaptation and flexibility

Ahmed, 2004	Community	The development of material, physical, socio-political, socio-cultural, and psychological resources that promote safety of residents and buffer adversity
Kimhi, 2004	Community	Individuals' sense of the ability of their own community to deal successfully with the ongoing political violence
Coles, 2004	Community	A community's capacities, skills, and knowledge that allow it to participate fully in recovery from disasters
Pfefferbaum, 2005	Community	The ability of community members to take meaningful, deliberate, collective action to remedy the impact of a problem, including the ability to interpret the environment, intervene, and move on
Masten, 1990	Individual	The process of, capacity for, or outcome of successful adaptation despite challenging or threatening circumstances
Egeland, 1993	Individual	The capacity for successful adaptation, positive functioning, or competence…despite high-risk status, chronic stress, or following prolonged or severe trauma
Butler, 2007	Individual	Good adaptation under extenuating circumstances; a recovery trajectory that returns to baseline functioning following a challenge

Source: Norris, Stevens et al. (2008)

Resilience Frameworks in the Literature

Many of the nuances in definitions of resilience arise when developing frameworks for analyzing resilience and community risk. A system-of-systems approach disaggregates a system into its constituent parts, which are linked together in subsystems, and those subsystems themselves are linked to each other. Since the transportation system is embedded within the larger socio-economic system-of-systems and the network nature of the transportation system, we concentrate our efforts on characterizing the system-of-systems frameworks for resilience. The premise is that individual subsystems can be isolated to carry out specific functions; thus, the approach is a way of viewing independent subsystems as part of a larger, more complex system.

Systems-based Approaches to Resilience

In considering the different frameworks that have been used, our approach builds on the work of da Silva and Morera (2014), which was used to develop the City Resilience Framework and City Resilience Index. As da Silva and Morera explicitly say, "systems based approaches align more closely with the concept of resilience, and the long-standing notion of cities as 'systems of systems.'" However, they review studies only on subsystems rather than those on the system as a whole, which leaves the interdependencies that arise across systems mostly unconsidered. In contrast, the National Institute of Standards and Technology (2015) provides a broad overview of the components of community resilience from a system-of-systems approach and explicitly includes a chapter on these cross-system dependencies.

Da Silva and Morera state the following about resilience and systems:

> Every city is unique. The way resilience manifests itself plays out differently in different places. The City Resilience Framework provides a lens through which the complexity of cities and the numerous factors that contribute to a city's resilience can be understood.

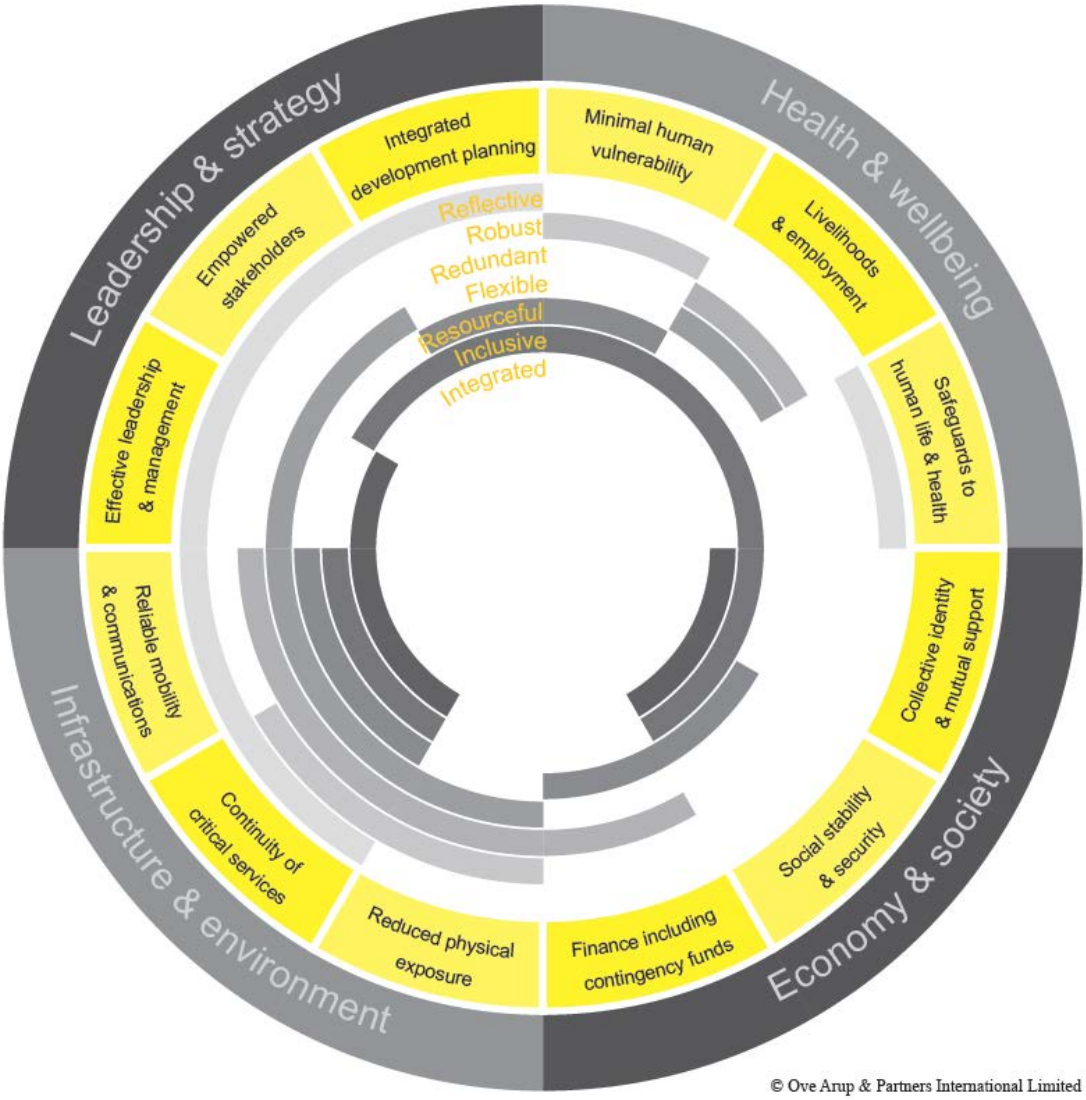
According to da Silva and Morera, resilient systems possess seven main qualities:

1. Reflective: Mechanisms that continuously evolve
2. Robust: Anticipation of potential failures, provisions to ensure failure is not disproportionate to cause
3. Redundant: Spare capacity to accommodate disruption, pressure and change
4. Flexible: System can change, evolve and adapt
5. Resourceful: People and institutions are able to rapidly find different ways to achieve their goal
6. Inclusive: Community engagement
7. Integrated: Integration and alignment between systems to promote consistency

In a unifying framework depicted in Figure 3.1, da Silva and Morera show linkages across the various components of leadership and strategy, health and wellbeing, economy and society,

and infrastructure and environment through the seven qualities of resilient cities. This framework integrates the individual systems through various channels.

Figure B.1. City Resilience Framework



Source: da Silva and Morera (2014)

According to Rodin (2013), resilient cities have five characteristics:

1. The capacity for robust feedback loops that sense and allow new options to be introduced quickly as conditions change.
2. The flexibility to change, and evolve, in the face of disaster.

3. Option for limited or “safe” failure, which prevents stressors from rippling across systems—requiring islanding or de-networking at times.
4. Spare capacity, which ensures that there is a backup or alternative when a vital component of a system fails.
5. The ability for rapid rebound, to reestablish function quickly and avoid long-term disruptions.

The list of characteristics of resilient cities from the work of Rodin and colleagues aligns well with those of da Silva and Morera.

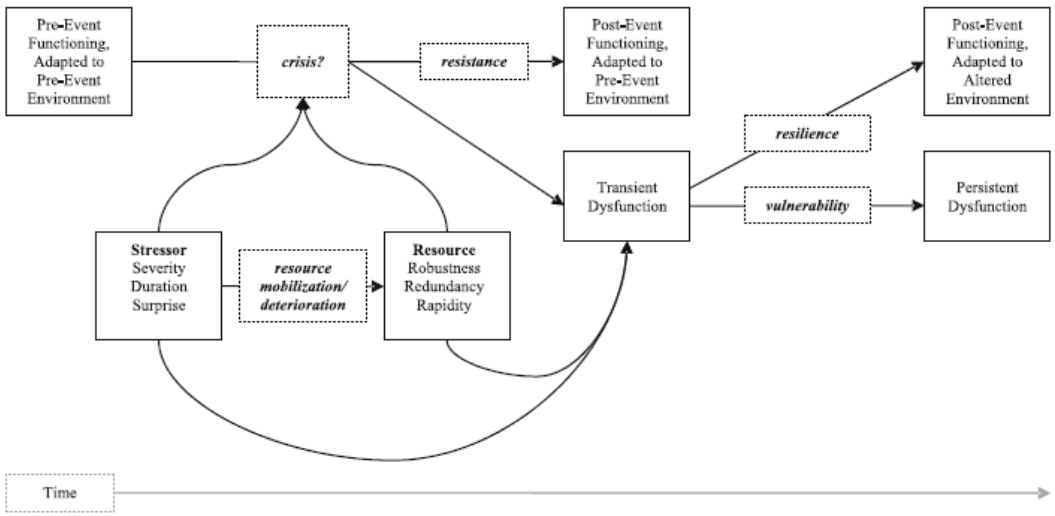
Several other frameworks also deserve individual consideration. Most of them approach disasters as problems of risk management within a system-of-systems framework combined with some form of either risk management or resilience. The major differences are the detail and connections among the different systems and subsystems that they present. An initial segmentation of a community into systems generally follows one of two approaches. First, some frameworks (e.g., Ziyath et al., 2013) distinguish among the ecological, economic, infrastructural, institutional, and social systems. Others (e.g., Bruneau et al., 2003) distinguish among the different infrastructural systems: hospital, electrical, water, local emergency management, and other systems. As discussed by Kahan et al. (2009), knowing the goals of the efforts to increase resilience are paramount to constructing a framework suitable for moving analysis and decisionmaking forward. This was echoed in our interviews with stakeholders in Chapter 2

Norris’s Resilience Framework

Norris and colleagues (2008) provide a useful starting point to consider alternative frameworks that inherently consider resilience (see Figure 3.2). First, a stressor is applied to the system. This stressor can vary in severity, duration, and time to warning. The resilience of the system determines if this stressor pushes the system to crisis situation that is similar to shocks that the system can absorb shock, or if the system has sufficient redundancy to absorb the shock through alternative channels. If the system is in crisis—meaning that a shock or impact changed the system’s pre-event conditions—then the system can take two alternative paths: Either the system will function, but adapted to a post-event world, or the system will have residual dysfunction. If the system is dysfunctional at this point, it can, again, take one of two paths. The system’s ability to adapt to the changed environment together with the system’s ability to recover determines whether the system can adjust to the changed environment. Though Norris’s framework fails to account for feedback when a disruption has occurred, its setup does take into account the three major elements of resilience: adaptation, absorption, and recovery. Additionally, Norris’s framework does not recognize that post-event functioning following one event is the pre-event functioning for the next event. This feedback is important as we consider community efforts to increase resilience to the next event from post-event funding opportunities that arise. As discussed by Godschalk (2003), when events occur in communities, learning takes

places both within and across these communities as to how better to recover from those events and prepare for future events.

Figure B.2. Norris et al. (2008) Framework of Resilience



Source: Norris, Stevens et al. (2008)

Rose's Framework and the Economic Impact of Mitigation

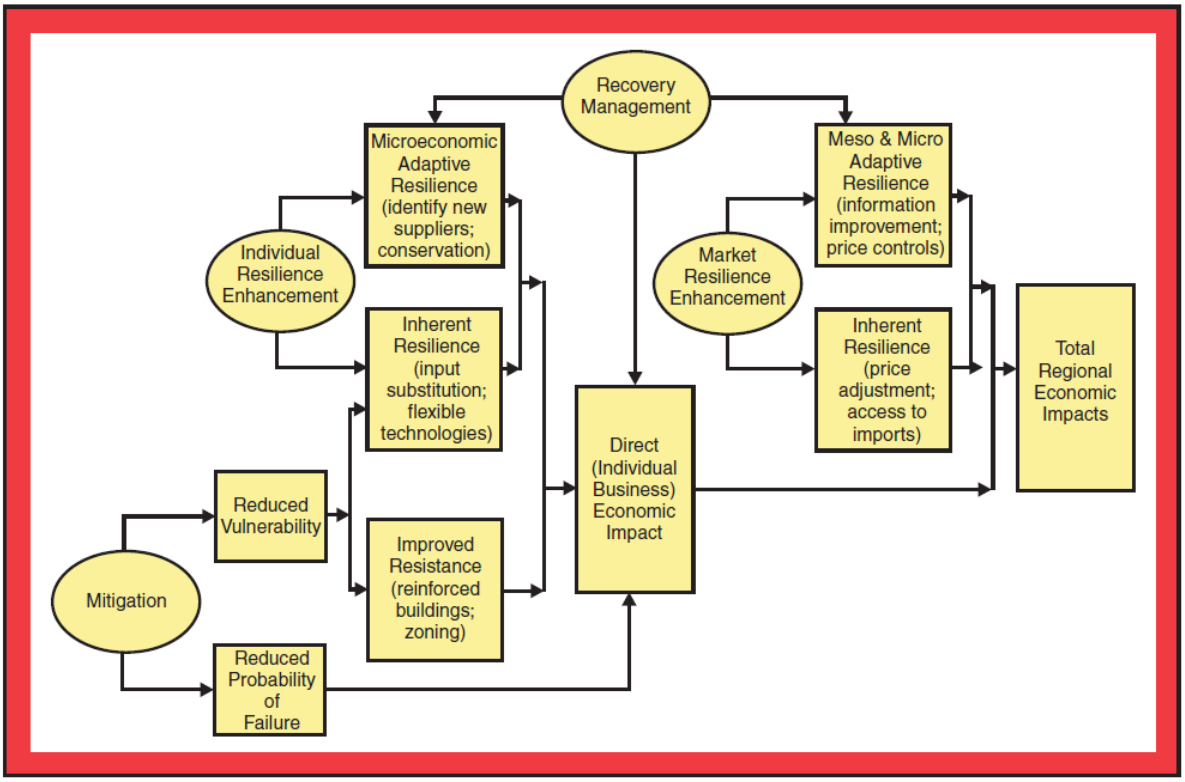
Rose (2004) developed a framework (Figure 3.3) that is similar in structure to Norris's but more detailed. The focus of Rose's framework is to understand the role of mitigation activities on total regional economic impact. Because of its focus on the economic impact, this framework considers only the community's economic subsystem and not the broader social and natural environments, although the framework could easily be adapted to incorporate such considerations. Rose's framework was specifically developed to assess how a system can be modeled to predict potential impacts, and to consider the appropriate measure of resilience. The framework's overarching goal is to minimize total regional economic disruptions, which are modeled using a general equilibrium model. Focusing on the economic subsystem reveals several different roles for adaptation that could be applied in a broader framework.

The key insight from Rose's framework is that community resilience is a function of household resilience, firm resilience, and system resilience, but is neither additive nor multiplicative among these subsystems. In particular, a mitigating strategy first affects the direct impact that an event may have. Hence, mitigation operates first to reduce the risk that a disruption will take place. Next, individuals and firms adapt to a changed environment by changing as necessary the inputs they use to produce goods and services and, ultimately, community well-being. How flexible the system is, inherently, and how the system is enhanced through the mitigating activities of firms and individual households determines the system's

inherent level of resilience. Once the initial adaptation takes place, recovery begins through a reconstruction of capital that was lost to the disruption and through alternative production functions that may be inherently more flexible and responsive to price signals that the system sends to the firms and households. In other words, how individuals and firms behave before, during, and after a shock (or in the presence of a stressor) serve as mitigating factors that influence the resilience of the system.

Although Rose uses a different definition of resilience—namely, "the ability or capacity of a system to absorb or cushion against damage or loss"—the three major aspects of resilience (absorptive, adaptive, and restorative capacity) are embedded in his ideas of inherent resilience and adaptive resilience as subcategories of resilience. Rose's view of resilience is that it is a property of the system and that it can be thought of at various spatial and organizational scales. Additionally, given the computable general equilibrium modeling that he uses, the linkages across sectors are also considered. If infrastructure is damaged, it affects a variety of sectors and the impact cascades through the system due to the effects on both upstream and downstream supply chains. Additionally, Rose is able to estimate the inherent resilience of a system due to the effects of mitigating activities and then to improve understanding of how investments affect resilience.

Figure B.3. Rose (2004) Framework



Source: Rose (2004)

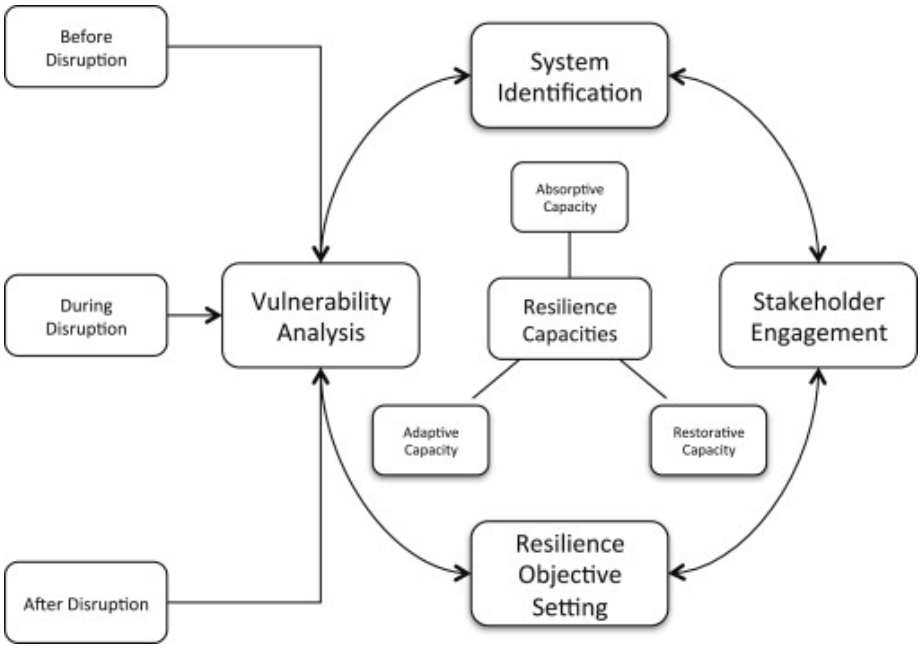
Francis and Bekera Framework Focuses on Goals and Metrics

Combining the Rose and Norris approaches, Francis and Bekera (2014) developed a framework that is more easily incorporated into a decisionmaking process. The Francis and Bekera framework has five main components (Figure 3.4).

1. System identification
2. Vulnerability analysis
3. Resilience objective setting
4. Stakeholder engagement
5. Resilience capacities

Two main characteristics distinguish this framework from those previously considered. First, this framework explicitly discusses the goals or objectives of increasing resilience, which is vital. The goals dictate the metrics that will measure progress toward increasing resilience. Without knowing the goals, progress or success cannot be assessed. Second, only this framework includes stakeholder engagement. Additionally, the framework explicitly shows the three elements of resilience (adaptation, absorption, and recovery) as well as the definition of resilience used in developing the framework. This framework incorporates risk governance explicitly through stakeholder engagement and objective setting as well as vulnerability analysis.

Figure B.4. Francis and Bekera (2014) Framework



Source: Francis and Bekera (2014)

Berke and Smith's Framework for Plan Quality Focuses on Internal and External Consistency

Berke and Smith (2009) provide 10 principles of plan quality for hazard mitigation that also could serve as a framework for resilience when moving from conceptual idea to practical implementation:

8. Issue identification and vision
9. Goals
10. Fact base
11. Policies
12. Implementation
13. Monitoring and evaluation
14. Internal consistency
15. Organization and presentation
16. Inter-organizational coordination
17. Compliance

The first six principles contribute to the seventh, internal consistency, and the last three contribute to external consistency. The key difference between the Berke and Smith approach and that of Francis and Bekera is that Berke and Smith focus on consistency across the community as well as monitoring and evaluating progress toward the goals identified.

Cutter's Distinction Between Vulnerability and Resistance

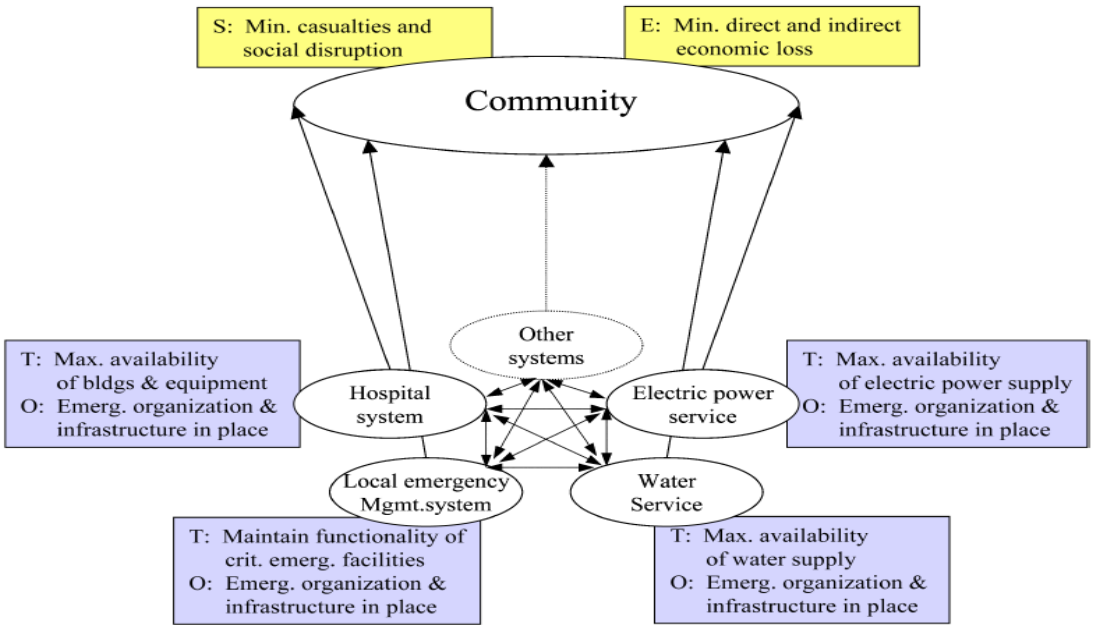
Another perspective, that of Cutter and colleagues (2008, 2003) explicitly distinguishes between vulnerability and resilience. The major difference between the frameworks we have already discussed, and the work of Cutter is that vulnerability and resilience are distinct but interrelated concepts for Cutter. Cutter's view is that resilience focuses on the adaptive nature of the system and not on the vulnerabilities embedded within it. Taking a broad view of resilience that encompasses the adaptive, restorative, and absorptive capabilities of the system may reveal complementarities among these definitions that can improve the well-being of a community. By making this distinction between vulnerability and resilience, these potential complementarities may be lost. One key point the Cutter work recognizes is the link between resilience and sustainability: Sustainability is a large component of resilience, especially when considering the idea of resilience of place and the policy definition that incorporates "with limited outside assistance." Resilience can be thought of as a more encompassing idea than sustainability but linked idea in terms of post-disaster adaptation and recovery.

Bruneau's Focus on Critical Infrastructure

Unlike the previous frameworks, that of Bruneau and colleagues (2003) focuses on critical infrastructure systems as opposed to social, economic, natural, and built systems (Figure 3.5). The starting point for Bruneau's analysis is that resilience has four dimensions: technical (T),

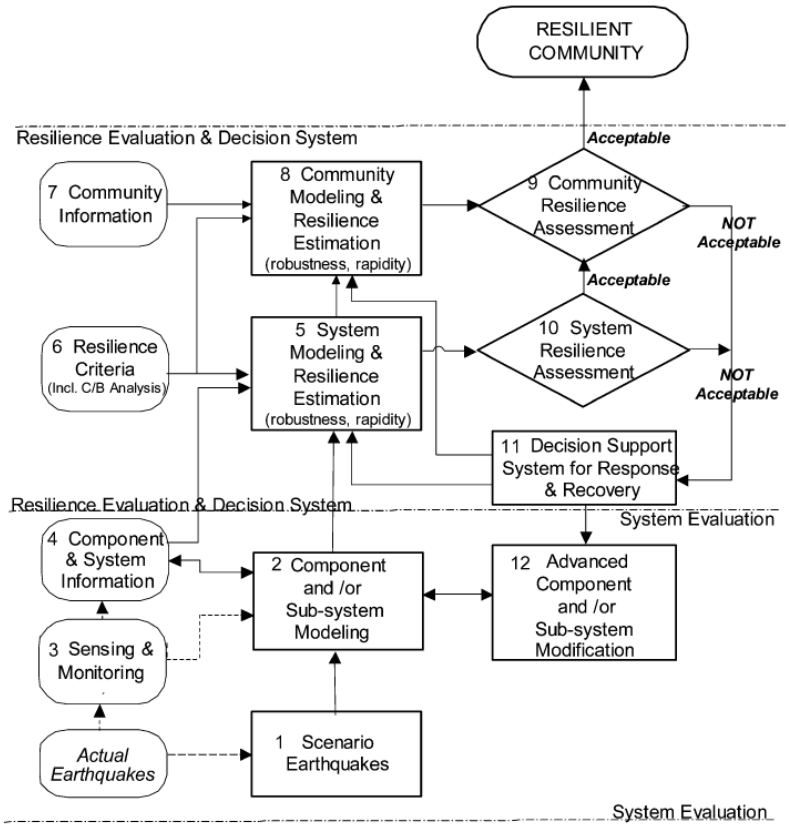
organizational (O), social (S), and economic (E). This TOSE framework places critical infrastructure in the overall resilience of a community through technical and organizational dimensions. The interdependencies within the critical infrastructure are key to understanding how events may cascade through the system, which many of the other frameworks fail to recognize explicitly. These interdependencies are captured through the social and economic systems that overlay the critical infrastructure. The larger framework contains two major distinctions that allow for analysis (Figure 3.6). First, the individual subsystems are analyzed. Then, these subsystem analyses are incorporated into a larger, community-level analysis that considers the joint determination of the larger system. In addition to those two points of analysis, the framework explicitly incorporates decision support as a subsystem within the larger system. An inherently iterative process continues within the decision support subsystem to continually modify the system until an acceptable level of resilience is achieved.

Figure B.5. Bruneau Framework



Source: Bruneau et al. (2003)

Figure B.6. Interrelationships in the Bruneau Framework



Source: Bruneau et al. (2003)

Vulnerability as the Focus of Turner's Framework and Challenges with System of systems Views

Though focused on vulnerability, Turner and colleagues (2003) developed a framework that is similar in spirit to that of Norris (2008) but that distinguishes between vulnerability and resilience as in Cutter.

One of the main problems with the systems-of-systems frameworks for analyzing resilience is that as more systems are added, complexity increases, complicating our understanding of all the elements and relationships between them. Some frameworks quickly become muddled when trying to move from a conceptual framework to actual implementation, since every system affects every other system.

Additionally, Haimes (2009) notes that because threats have a particular risk of occurring, and because each possible consequence of the threat has a certain possibility of occurring, it is important to be able to weigh the total costs of these risks against the costs of investing in preparedness and resilience.

An essential part of community-based decisionmaking is recognizing that multiple goals result in inevitable tradeoffs among these goals that need to be considered when thinking about investments in resilience. With their attention to power structure, governance processes are the mechanism for assessing these kinds of tradeoffs. Given communities' finite budgets, they need a decision support tool for considering the tradeoffs and complexities of investments in resilience. To be useful as a decision support tool, a framework must incorporate the tradeoffs that the community is facing when building resilience. This decision support tool should not make the decision for the community but should provide a level playing field for all participants in the decisionmaking process.

To obtain accurate tradeoffs, the decision support tool must incorporate the spillover of resilience in one subsystem to the other subsystems, along with the direct effect on the subsystem. Importantly, the interdependencies of systems matter. To determine the total effect of investments in resilience made in one subsystem, one needs to measure the direct value to that subsystem as well as the indirect value—a reduction in the probability of disruption to other interdependent systems. This approach is very similar to that of Rose and others (2004) that have used input-output and computable general equilibrium type models that can simulate the interdependencies within the supply chain. This approach is also readily seen in the NIST framework, which explicitly incorporates interdependencies that affect the recovery process (NIST, 2015). These interdependencies are more easily seen when the systems are segmented by function (e.g., electrical, water, waste water systems) than when segmentation of the system occurs across social, economic, physical, and other lines.

Mayunga (2007) proposes an alternative view. Similar to the literature on economic sustainability, this view focuses explicitly on capital, rather than systems. It considers investments in resilience to be investments in various capital stocks that are used together to increase resilience. This focus on capital is also the implicit focus of most of the scorecard or indicator systems, but few acknowledge this perspective in the development of their conceptual frameworks for resilience.

Like weak sustainability (Pearce and Atkinson 1993), resilience increases are the value of the increase in total capital stock where the values of different capital stocks are interrelated, not separable as they are in the sustainability literature. Similarly, the absorptive, adaptive, and restorative capacities of resilience might be viewed as a different segmentation of the capital stocks. Important substitution and complementary relationships among capital stocks impact resilience that stems from the interdependencies.

Indicators and Metric Systems

Indicators and metric systems are a bridge between the conceptual frameworks and the decision support tools. This section presents an overview of the literature on resilience metrics, largely informed by the comprehensive review on the same subject by Cutter (2016).

Many alternative indicator and metric systems have been used to measure resilience of communities. There are four main reasons that a community may want to develop or use a resilience indicator or metric system. First, they may help characterize the system and bring awareness to the community of its shortcomings (Prior and Hagmann 2014). Second, they may provide a means to develop baselines and assess the progress of the community toward its goals. Third, they may provide a broader view of the interdependencies of a system and how it reacts to various stresses on the system (Linkov, Bridges et al. 2014). Finally, metrics can be used in decision support and planning, but as Cutter (2016) states:

> While the arguments can be made on the importance of measuring resilience, the devil is always in the details. For example, there is no panacea, or one size fits all tool to measure resilience due to the range of actors, environments, purposes and disciplines involved. Instead, the landscape of resilience indicators is just as diverse as the systems, communities, or disasters that are studied (p. 743).

It is difficult to develop a single system of metrics that can characterize the resilience across vastly different communities with vastly different exposures and risks. Additionally, most of the suites of indicators segment the systems rather than developing the interdependencies and potential for cascading effects that underlie most of the frameworks. There appears to be a disconnect between the frameworks of resilience and their practical implementation in tandem with systems of indicators. The frameworks all strive to incorporate these interdependencies while most of the indicator systems do not take them into account but only consider indicators of subsystem resilience without the interconnections.

Cutter (2016) provides the most comprehensive overview of the wide variety of indicator systems that have been used to date. She considers 27 different approaches that have moved from conceptual systems to that of being implemented by at least one community. From these 27 systems, Cutter segments them along a number of different dimensions. First, she segments them into three categories: indices, scorecards, and tools. Indicators are often combined to create an index through statistical means. Scorecards provide a means to evaluate progress toward a goal usually through qualitative rather than quantitative methods.

She further segments indicator systems into top-down vs. bottom-up approaches. Top-down approaches allow for comparison across communities whereas bottom-up approaches are specifically tailored to the community where the assessment is taking place. One of the common characteristics of the systems identified by Cutter are that most of them develop indicators for the social, economic, institutional, infrastructure, and natural systems but lack links between these systems. From a systems-of systems approach and all of the frameworks previously considered in this report, the systems isolate the systems rather than considering the cascading effects and interdependencies that are inherent in resilience generally.

In addition to the review by Cutter, several other reviews, including Brooks, Aure et al. (2014), Link et al. (2015), and Winderl (2015), assess resilience metrics. Brooks et al. note that indicator systems are themselves conceptual frameworks. The focus of the Link et al. study was

on developing a national-level resilience scorecard and reviewed many of the same sets of systems as Cutter. The Winderl study findings, similar to those of Cutter, focus on measuring the resilience of subsystems rather than at the larger community level. In work sponsored by the Department of Homeland Security, MITRE (2016) catalogs indicators of resilience that have been used in many applications and segments them according to the economic, social, infrastructure, institutional, community capital, environmental, educational, and health systems that were identified in Cutter's work.

In addition to the systems discussed in the reviews above, there are a number of different resilience indices that have also been considered. Rose (2007) considers the resilience of an economic system to shocks. Rather than focus on the individual systems that make up an economy, Rose focuses on the aggregate outcomes of production. By focusing on production, the supply chain networks within an economy can be captured in a relatively straightforward manner. Rose calculates the difference between how the system would react with and without accounting for interdependencies. This approach has been used to estimate the impact of water distribution system disruptions (Rose and Liao, 2005), electric power disruptions from terrorist attacks (Rose, Oladosu, and Liao, 2007), and the ARkStorm Scenario (Wing, Rose, and Wein, 2015). This method could be further expanded by adding additional components to a general equilibrium model, incorporating environmental outcomes and using models of the built environment to estimate capital impacts.

Critique of the Literature on Metrics

One of the main problems that we see with the current systems of metrics is the segmentation of the evaluation of individual subsystems. The network effects that occur across subsystems, which are the cornerstone of the resilience view, seem to be omitted. For example, the Rose approach takes into account these network interactions but only for the economic and infrastructure systems that are explicitly modeled. Additionally, the Rose approach uses a single metric to define resilience of the system: relative difference between maximum lost productivity with no adaptive capacity and lost productivity following a shock with adaptive capacity. Although this system is economic-centric, it can incorporate other dimensions that are interdependent with the economic system. This approach would also allow for the evaluation of the tradeoffs between different investments in increasing resilience given the single metric. In developing a decision support tool, one of the main contributions should be a better ability to understand the tradeoffs that the system allows due to its interdependencies and networks.

Cutter (2016) suggests, two main approaches that can be used to develop indicator systems, either top-down or bottom-up. The distinguishing characteristic is whether the system is tailored to a particular community or is more general across a range of communities. Also, the individual metrics for the subsystems overlap extensively, and the specific indicators used in the systems identified by Cutter have only minor differences, whether they use a bottom-up or top-down

approach. These metric systems do not match the frameworks being developed for the analysis of resilience.

The overriding theme of the indicator systems is that if the subsystems are resilient, then the system is resilient. This is a significant assumption and one that misses a point often made in the resilience literature that there are cascading consequences across the system. This flaw is also found in the literature that measures the vulnerability of a system in the absence of considerations about exposure and hazards. A community may be vulnerable when measured using the Social Vulnerability Index (SoVI) (Cutter, Boruff et al. 2003), but if it does not face any hazards, is it really vulnerable? Similarly, one subsystem may not be very resilient, but it may also not be an integral part of the community so that it does not impact the overall resilience of the community to a great extent. We must view the resilience of a system as more than the sum of its parts. Through better understanding of the interdependencies and metrics associated with those interdependencies, a more thorough understanding of the resilience of a community can be had. The indicator systems and indices need to better incorporate the frameworks that they are trying to measure rather than simply focusing on the components that make up the system.

Focusing on the resilience of subsystems is insufficient to measure the resilience of the entire system, but we found that resilience metrics in the literature generally do not account for interdependencies across subsystems. Further, we were unable to identify articles that provided a validation of the indicator or metric systems. That is, the indicators and metrics that have been considered and used in many different systems are presumed to be correlated with resilience but there have been no empirical assessments, to our knowledge, that this is the case. Using the recovery process from Hurricane Katrina and Superstorm Sandy as natural experiments to compare across communities has been discussed, but little to no work has been done to see if communities that have higher levels of resilience based on any resilience metric recover more quickly or to a higher level of functioning.

Recent work by Gao, Barzel et al. (2016) developed a method to collapse multi-dimensional complex networks into a single summary metric of resilience. In their metric, it is the network topology that determines the resilience of the system while the individual subsystems play a more minor role in overall resilience. The authors assert that the three key factors in assessing the resilience of a system are the density of the connections in the system, the heterogeneity of those connections, and the symmetry. A more resilient system, all other conditions assumed to be the same, is one that has many connections including redundant ones, is heterogeneous in the number of connections between subsystems, and has relative symmetry: if subsystem A impacts subsystem B then subsystem B impacts subsystem A. Additionally, the matrix that summarizes the strength and presence of a connection between two subsystems can be used as a weighting matrix in the development of an index of resilience that comes from indicators of resilience of the subsystems. Rather than relying on simple averaging or factor analysis to provide weights, the system's actual characteristics and network could be used to form an index of resilience.

Having said that, single indices tend to reduce information available to decisionmakers rather than enhance understanding. Weighting is a function of the values of the individual setting the weights and thus is part of the public discourse about trade-offs among multiple competing public objectives.

Summary

All of the frameworks within the system-of-systems literature provide different approaches to tackling roughly the same problem of how to conceptualize a large number of independent systems that interact either through functional segmentation or infrastructural segmentation. Each of these frameworks appeal to different types of analyses as well as different views about the world. The Rose framework provides a useful starting point, if only focused on the economic system, for considering the interactions that occur and how adaptation could be enhanced. Norris *et al.* provide an intuitive approach for how resilience can be explained across different stakeholders and how investments at different locations can enhance the outcome stemming from a disruption. There is no lack of conceptual frameworks but there are commonalities in that the resilience of the set of subsystems does not imply the resilience of the entire system and that the interdependencies matter to the resilience of the whole. The key is finding a balance between detail and parsimony to understand how different investments and disruptions cascade through the entire system. The design of the framework should simplify its use and highlight where "touch points" between systems exist rather than focusing on all the potential relationships that may take place in a community.