Incorporating Resilience into Transportation Planning and Assessment

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Preface

This report was initiated to explore how to incorporate resilience into long-term transportation planning for state departments of transportation and metropolitan planning organizations and to inform the Transportation Research Board (TRB)—a division of the National Research Council of the National Academies of Sciences, Engineering, and Medicine—about our findings. In this report, we consider not only the specific hazards associated with climate change but also all hazards, focusing on stresses to transportation systems that arise naturally but might be exacerbated by disturbances to the system, such as congestion. This work was sponsored by TRB under the National Cooperative Highway Research Program project 08-36, Task 146.

We used a two-pronged approach to develop a conceptual framework for incorporating resilience into transportation planning and implemented both prongs in parallel. The first prong consisted of interviews with stakeholders at state departments of transportation and planners in metropolitan planning organizations intended to better understand the role that transportation resilience plays in practice. The second prong consisted of reviews of the published literature on transportation resilience, resilience more broadly, and metrics associated with both transportation and resilience. Using the interviews and literature review, we developed a logic model to map transportation system assets: transportation activities, transportation outputs and outcomes, and, finally, socioeconomic outcomes. This logic model, together with more-traditional views of resilience, informed the development of the absorptive capacity, restorative capacity, equitable access, and adaptive capacity (AREA) interpretation of resilience for transportation. We then used the AREA approach to develop a suite of metrics that correspond to different aspects of resilience. In this report, we describe the development of our conceptual framework and offer suggestions for how state departments of transportation and metropolitan planning organizations could modify the Federal Highway Administration's Vulnerability Assessment and Adaptation Framework to better incorporate resilience considerations and all hazards and stresses into long-term decisionmaking for transportation.

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

Community Health and Environmental Policy Program

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Policy Program within RAND Social and Economic Well-Being. The program focuses on such topics as infrastructure, science and technology, community design, community health promotion, migration and population dynamics, transportation, energy, and climate and the environment, as well as other policy concerns that are influenced by the natural and built environment, technology, and community organizations and institutions that affect well-being. For more information, email chep@rand.org.

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Summary

This report provides an approach for incorporating resilience into transportation planning and assessment for state departments of transportation and metropolitan planning organizations. We build on the Federal Highway Administration's Vulnerability Assessment and Adaptation 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 transportation resilience and resilience metrics literature, we developed a simple conceptual framework to adapt resilience principles to transportation. The absorptive capacity, restorative capacity, equitable access, and adaptive capacity (AREA) interpretation of resilience contributes to this framework and provides a starting point for the 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 approach provides a means to discover alternative options or strategies that should be considered when planning to increase the resilience of the entire transportation system.

Recommendations

We make the following recommendations for implementing the VAF to incorporate more aspects of resilience:

- Expand the objectives and scope of the framework to include shocks and stresses that are not directly tied to climate change, including cyberattacks.
- Broaden the asset data to include human and equipment assets, use the logic model to guide expansions, and identify the criticality of these new assets.
- Expand hazard data to consider a wider array of hazards and determine whether they are systemwide or if they influence only a subset of assets.
- Use the indicators we identified to assess the resilience of the system in a way that acknowledges the interaction of the criticality and exposure of the assets.
- Engage stakeholders and decisionmakers to help weigh the trade-offs that come with prioritizing options.
- Use an established critique, such as multicriteria decision analysis, economic analysis, benefit-cost analysis, or life cycle cost analysis, to facilitate prioritization.
- Consider the benefits of investment in times of both normalcy and disruption.

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Abbreviations

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AREA	absorptive capacity, restorative capacity, equitable access, and adaptive capacity
DOT	department of transportation
FAST	Fixing America's Surface Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GIS	geographic information system
LRTP	long-range transportation plan
MAP-21	Moving Ahead for Progress in the 21st Century
MOR	measure of resilience
MPO	metropolitan planning organization
NIST	National Institute of Standards and Technology
SoVI	Social Vulnerability Index
TIP	Transportation Improvement Program
TRB	Transportation Research Board
TTTR	Truck Travel Time Reliability
VAF	Vulnerability Assessment and Adaptation Framework
VMT	vehicle miles traveled

1. Introduction

The Federal Highway Administration's (FHWA's) Vulnerability Assessment and Adaptation Framework (VAF) "is a manual to help transportation agencies and their partners assess the vulnerability of transportation infrastructure and systems to extreme weather and climate effects" (Filosa et al., 2017, p. i). Although this manual helps transportation planning agencies incorporate climate adaptation into their existing processes, it lacks a framework for incorporating resilience into the transportation planning process more broadly. For this reason, the Transportation Research Board (TRB) of the National Academies of Science, Engineering, and Medicine, which advises the nation on issues of transportation, tasked RAND Corporation researchers to develop an evidence-based framework for incorporating resilience into the implementation of the VAF and into transportation planning for state departments of transportation (DOTs) and metropolitan planning organizations (MPOs).

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 the 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 decisionmaking.

The focus of the VAF is on mitigating and adapting to vulnerabilities that arise because of climate change. More broadly, the VAF can be used to plan for and assess the resilience of the transportation system, not only to vulnerabilities because of climate change but also to shocks and stressors from other sources. Instead of developing a new resilience-centered planning and assessment framework, we offer a strategy focused on resilience that uses the VAF as a backdrop for implementation. Because organizations might have experience with the VAF, our approach simply incorporates resilience into a broader suite of vulnerabilities. Our implementation strategy is to view the assets in a transportation network through the absorptive capacity, restorative capacity, equitable access, and adaptive capacity (AREA) lens to allow for more strategies to increase the system's 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 it is but one system in the larger socioeconomic system. Additionally, transportation is a means to an end rather than 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 could contradict or miss key aspects of the value of the transportation system in times of stress or shock. Therefore, our approach for better integrating 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 incorporate resilience into long-term systemwide planning and the decisionmaking process more easily.

We make the following recommendations for implementing the VAF to incorporate more aspects of resilience:

- Expand the objectives and scope of the framework to include shocks and stresses that are not directly tied to climate change, including cyberattacks (see Table 3.1 in Chapter 3).
- Broaden the asset data to include human and equipment assets, use the logic model to guide expansions, and identify the criticality of these new assets (see Figure 3.4 in Chapter 3).
- Expand hazard data to consider a wider array of hazards, including cyberattacks, and determine whether they are systemwide or if they influence only a subset of assets (see Table 3.1 in Chapter 3).
- Use the indicators we identified to assess the resilience of the system in a way that acknowledges the interaction of the criticality and exposure of the assets (see Chapter 4).
- Engage stakeholders and decisionmakers to help weigh the trade-offs that come with prioritizing options (see Chapter 2, Appendix A, and Appendix B).
- Use an established critique, such as multicriteria decision analysis, economic analysis, benefit-cost analysis, or life cycle cost analysis, to facilitate prioritization (see Chapter 2 and Appendix B).
- Consider the benefits of investment in times of both normalcy and disruption (see Figure 3.3 in Chapter 3).

We used a two-pronged approach to develop a conceptual framework for incorporating resilience into transportation planning and implemented both prongs in parallel. The first prong consisted of interviews with stakeholders from MPOs and state DOTs to assess the state of resilience in transportation and understand how stakeholders use information on the costs and benefits of resilience when making long-term investments in highway and transportation infrastructure. The second prong consisted of a review of the literature on resilience with a focus on system-of-systems frameworks, literature on defining and incorporating resilience into transportation planning, and metrics for transportation resilience. In addition, a research team member attended the Transportation Resilience Innovations Summit and Exchange in Denver, Colorado, in 2018. The goal in attending the conference was to understand the dialogue around transportation resilience among key stakeholders, including state DOTs, MPOs, transportation consulting organizations, academics, and others who focus on resilience in transportation. This approach informed our conceptual framework and provided context for 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. The *transportation network* includes not only infrastructure assets but also the approximately 4,200 people who work for MPOs across the United States and the 50 state DOTs (Kramer, Carroll, and Karimi, 2017). Embedding the framework in this broader system-of-systems perspective helps planners discover alternative options or strategies that should be considered during planning to increase the resilience of the transportation system.

There is neither a single theory that provides a conclusive definition of resilience nor a widely accepted practice for achieving resilience. From some perspectives, resilience is not a measurable outcome at all; rather, it is a way of approaching all aspects of a system over the course of the life cycle of a project, from planning to operation and maintenance. Presidential Policy Directive 21 provides federal perspective, defining resilience for critical infrastructure as

> the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents (The White House, Office of the Press Secretary, 2013, p. 12).

The Fixing America's Surface Transportation (FAST) Act, which was signed into law in December 2015, requires planners to consider resilience and, specifically, stormwater during the planning process (Pub. L. 114-94, 2015). Although the FAST Act requires resilience to be considered, it does not provide guidance for how to incorporate resilience into the planning process. Furthermore, different communities face different shocks and stresses on their transportation infrastructure. Thus, the aim of this report is to provide guidance to transportation planners for how resilience might be incorporated into the assessment of and planning for transportation infrastructure.

Using our reviews of the literature and interviews with transportation stakeholders, we have developed a logic model for mapping the transportation system assets to activities, outputs, and outcomes, as well as to community well-being. By mapping the system, we are better able to capture how modifying the system translates into outcomes that planning organizations are trying to improve. We then combine this system mapping with a multidisciplinary view of resilience to develop a framing of resilience for that transportation system: the AREA approach to resilience. Each of the AREA dimensions of resilience suggests a means through which to increase the resilience of the system, although by different methods. Importantly, the networked nature of the transportation system means that the aim of investment in resilience is to reduce reliance on individual assets or reduce the assets' exposure so that cascading effects across the network are mitigated. That is, resilience investments should improve the operation of the network during both normal and disrupted times and avoid 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, which we discuss in Appendixes A and B. In Chapter 3, we develop our logic model and conceptual framework. In Chapter 4, we summarize metrics that could be used for measuring resilience based on the AREA approach. In Chapter 5, we incorporate our conceptual framework into the implementation of the VAF. Finally, in Chapter 6, we provide some general conclusions for planners about incorporating resilience into the transportation system. As noted earlier, we provide detailed overviews of our interviews with stakeholders and the literature review of resilience in Appendixes A and B, respectively.

2. Resilience in a Transportation Context

In this chapter, we summarize the results of our two-pronged approach for reviewing how resilience has been considered in transportation. First, we describe our discussions with transportation experts. Second, we discuss our broad literature review of resilience and how resilience has been applied to transportation specifically. We provide more details on our stakeholder interactions in Appendix A. In Appendix B, we provide additional information about resilience from the literature. Building on these two approaches, we focus on how resilience is used and applied in a transportation context. We begin by discussing how the transportation community defines, measures, and incorporates resilience into transportation decisionmaking. Next, we discuss how transportation planners consider equity and nontransportation benefits. Finally, we examine who benefits from transportation infrastructure.

Stakeholder Interviews

The stakeholders that we spoke with were from organizations directly involved with transportation infrastructure planning and investments through implementation, planning, or policy, such as MPOs, state DOTs, and federal transportation offices and committees. We conducted nine interviews with eight organizations. There were four MPOs in Florida, Louisiana, Tennessee, and Texas; two state-level DOTs in Colorado and Iowa; and two federal-level organizations based in Washington, D.C. We reached out to organizations from various regions of the United States in order to glean insights from those facing different geographies and contexts, although some organizations did not respond or declined to participate. Stakeholders that were interviewed provided valuable information about how transportation planners and policymakers implement resilience and what is needed in the future to ensure a more resilient transportation system.

Our interviews included discussions of other organizations that stakeholders interacted with for transportation planning, both within and outside the transportation system. This was important to capture because it relates to both transportation system outcomes and broader socioeconomic outcomes. Other topics discussed included the stakeholders' priorities; the benefits, costs, and challenges they consider; how they use available information to inform long-term planning and investments in infrastructure; their perspectives on what is needed for the system to become resilient or maintain resilience; and their thoughts on how transportation resilience is defined and measured.

The priorities noted by stakeholders relate to maintaining current infrastructure; facilitating quick restoration of infrastructure following disruptions; and updating or adding such services as public transportation to improve outcomes, including congestion, safety, environmental impact, and job access. Interviewees highlighted that transportation infrastructure and services contribute to benefits beyond the transportation system: Transportation affects other social, economic, and environmental systems. Stakeholders noted that they work with different types of organizations, including businesses, medical districts, hospitals, public health department divisions for water and air quality, and commissions that reach out to special-interest groups. Interviewees also noted that they work across different levels of government, including in the counties and jurisdictional governments where they are located and in neighboring jurisdictions.

Interviewees also described challenges that can limit the ability of the transportation system to provide benefits, highlighting disruptions to which transportation systems should be resilient. Such challenges include disruptions and risks related to extreme weather events (i.e., flooding, high-level winds, storm surge); other environmental physical threats, such as rockfalls, land loss and erosion; infrastructure outages; and human-induced threats, such as cybersecurity threats or even population growth in terms of increased demands on and needs for infrastructure. Challenges related to planning and implementation include limited funding, limited data for planning, lack of agreement on priorities among different levels of government, management turnover, slow adoption of new practices, lack of all-hazards planning, and underdeveloped public infrastructure. Stakeholders expected new challenges to arise in the future, such as autonomous vehicle adaptation, coordination among 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 next section, there is no single precise definition of resilience across all transportation agencies. Some of the stakeholders we interviewed had established their own definitions 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 to, recover from, and respond to—and bounce back quickly from—(1) threats to physical infrastructure and operations and (2) threats of cybersecurity, terrorism, and all hazards. Furthermore, it is the ability to minimize impact and ensure that the transportation system is still usable following a shock or stressor. Interviewees mentioned several factors that would contribute to resilience, including a culture shift toward promoting a national understanding of transportation resilience; cross-sector coordination for transportation planning and short-, medium-, and long-term strategies; clear policies and requirements to ensure that implementation, planning, and reporting are understood and implemented similarly for all transportation organizations; and improved understanding of the connectivity between transportation systems and critical assets. Other factors mentioned include data sharing; resilience-targeted funding; infrastructure redundancy; and knowledge of the impact of events, including on critical assets and on such systems as the economy.

Finally, although the interviewees did not have many quantitative metrics for measuring transportation system resilience and its impacts on socioeconomic and environmental systems, they did collect and monitor data as of the writing of this report. Examples of metrics stakeholders can access include data on crashes, community participation in transportation, asset inventory, infrastructure damage and cost and repair, road closure times, delay times, and congestion rates. Interviewees noted that they would like to have access to metrics and data related to resilience, including 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. A more detailed description of our stakeholder interviews can be found in Appendix A.

What Is Resilience?

The literature suggests three main themes associated with the concept of resilience: (1) reducing the likelihood of a disaster and increasing the ability of a community to absorb or resist a shock, (2) increasing the adaptability of a system while maintaining functions in the presence of a shock, and (3) reducing the time to recovery to normal functioning, which might be different from pre-event functioning. These themes translate into three 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 is a movement to incorporate equity or equitable access into resilience (Nicholls, 2001).

Generally, conceptual frameworks can be categorized into two groups: systems that segment by public-service sectors (e.g., electric, water, transportation) and systems that segment along functional lines (e.g., social, built, and natural environment). This segmentation can miss important interdependencies among 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 focus on the interdependencies. Decisionmaking around resilience forces communities to make trade-offs across many outcomes, and alternative frameworks help conceptualize those trade-offs. Importantly, system-of-systems approaches are frameworks that can be directly applied to transportation, either in isolation or in thinking about the socioeconomic system within which the transportation system is embedded. A more detailed discussion of resilience generally and conceptual frameworks for incorporating resilience specifically 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 to, recover from, and respond to a variety of threats to physical infrastructure, operations, cybersecurity, terrorism, and all hazards. 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" (U.S. Department of Transportation, FHWA, 2014). Many state DOTs and MPOs have similar definitions of resilience, according to our stakeholder interactions. Some definitions appear as informal statements in meeting minutes, while others are explicitly defined in transportation planning documents. Some examples of definitions of resilience include "reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs" (Minnesota DOT, 2017, p. 90); ensuring the ability of the transportation system "to quickly respond to unexpected conditions and return to its usual operational state" (Wisconsin DOT, 2009, p. 9-2), and ensuring "the ability of the transportation system to withstand and recover from incidents" (Tennessee DOT, 2015, p. 4). As noted by Dix and colleagues, 2018, p. 5, state DOTs and MPOs 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 in 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 variation in the definition of resilience is the type of disruption the transportation network is intended to avoid or quickly mitigate. Resilience is most commonly discussed in the context of natural hazards. However, some state 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 (e.g., rising fuel prices) or crime.[1]

How Does the Transportation Community Measure Resilience?

Given the lack of consensus on the definition of resilience both within and outside the transportation sector, it is unsurprising that no widely accepted metric exists for measuring transportation resilience. Although many transportation entities have working definitions of resilience, few have quantitative metrics to measure resilience. Ninety-two percent of the states surveyed by Flannery, Pena, and Manns, 2018, reported having no specific resilience metrics in place for transportation. A variety of possible metrics have been suggested and tested. For example, Parkany and Ogunye, 2016, suggests a series of potential metrics that are aligned with the four components of resilience outlined by Bruneau and colleagues, 2003 (robustness, redundancy, resourcefulness, and rapidity; see Table 2.1). In Chapter 4, we discuss the variety of metrics used to measure different aspects of resilience.

[1] For example, the Madison Area Transportation Planning Board in Wisconsin has a goal to "develop a transportation system that is resilient in the face of climate change and rising fuel prices in the future" and to "reduce [the] vulnerability of the public and the region's transportation infrastructure to crime and natural hazards" (Madison Area Transportation Planning Board, 2017, pp. 4-4, 4-6).

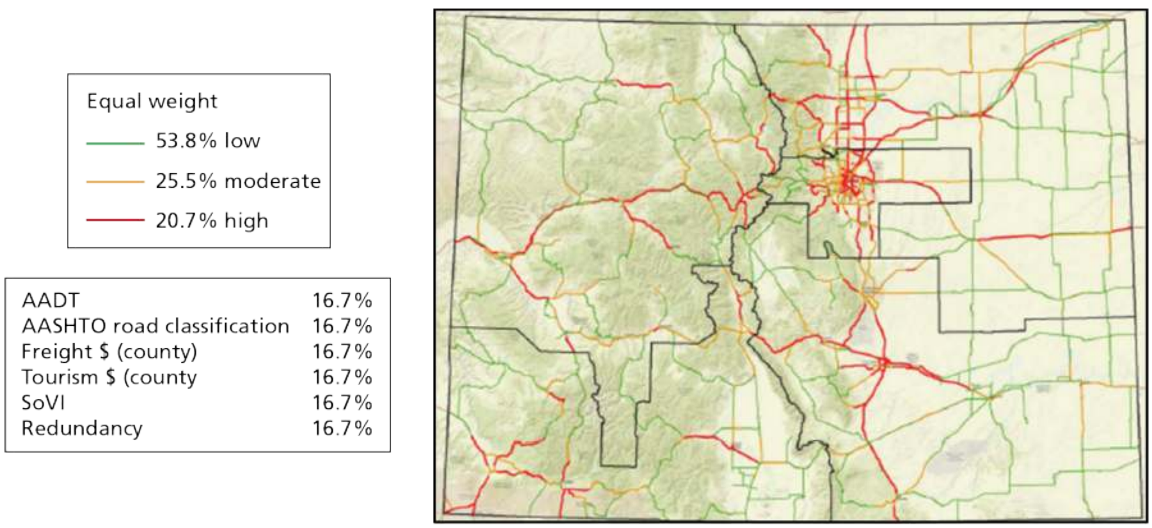
Table 2.1. Resilience Metrics, Based on Bruneau and Colleagues' Components of Resilience

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 alternate routes
	Percentage of corridor with alternate routes
	Available capacity on alternate routes
	Congestion on alternate routes
	Availability of alternate 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 alternate routes
	Construction projects
	Weather mitigation capability
Rapidity	Time until reopened or fully restored for top 5 percent incident
	Average construction project duration

There is a common desire among decisionmakers to combine measures of different aspects of resilience into a single representative number. Such one-dimensional measures might be enticing because they offer policymakers a simple way to prioritize across different aspects of resilience, but these indexes can lack the ability to communicate important nuances. Direct comparisons between different aspects of resilience are possible because decisions about trade-offs are made in the modeling process when different measures of resilience (MORs) are combined into a single measure. One example of a combined measure comes from research by the Colorado DOT and FHWA, 2017. This study provides a methodology to support investment decisions in Colorado's I-70 corridor. The first step in its resilience evaluation process was to assess asset criticality. Criticality for different roadway segments can be calculated by the evenly weighted combination scores of six different rankings: annual average daily traffic (AADT); the American Association of 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) scores at the county level (Cutter, Boruff, and Shirley, 2003); and system redundancy, as measured by the Colorado DOT'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 assigned "high criticality." If we take the inputs and weights as givens, this ranking provides a justification for where to focus resilience efforts in the evaluated system. Planners using this process would prioritize investments in high criticality segments over investments in low criticality segments.

Figure 2.1. Colorado DOT Asset Criticality Map



SOURCE: Adapted from Colorado DOT and FHWA, 2017.

These criticality scores are not a resilience metric, and Figure 2.1 is not a map of system resilience. Rather, it is a prioritization of roadway segments based on an aggregation of discrete qualities of those segments. Preferences among 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. However, 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 2017 Colorado DOT and FHWA study next examined the anticipated annual risk, or expected loss, for each potential hazard, calculated as:

$$Risk = C \times V \times T$$

where *C* is the total monetary loss 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 that the hazard will occur in a given year. The authors then examine various mitigation options and calculate the change in expected losses divided by the cost of the intervention, essentially performing a cost-benefit analysis.

Many states have programs for identifying and measuring risk, but few have identified funding sources for addressing those 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 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 in and between communities. Disruptions in the network reduce economic productivity, harming local commercial activities and tax revenues. Such disruptions also directly harm individuals' well-being by restricting their mobility or creating safety hazards. Therefore, 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 to be 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 regulation as a reason for including resilience in their transportation planning" (Dix et al., 2018, p. 8). Relevant laws include the FAST Act (Pub. L. 114-94, 2015), the Moving Ahead for Progress in the 21st Century (MAP-21) Act (Pub. L. 112-141, 2012), and the U.S. Department of Homeland Security National Infrastructure Protection Plan (U.S. Department of Homeland Security, undated).

Sections 1201 and 1202 of the FAST Act require that agencies incorporate resilience into the planning process. The FAST Act adds resilience to sections of the U.S. Code (particularly Title 23, Highways, and Title 49, Transportation). For example, 49 C.F.R. § 5303 (a)(1), 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 C.F.R. and 49 C.F.R. Some state laws also encourage or require the incorporation of resilience into transportation planning, such as California Executive Order B-30-15 (Office of Governor Edmund G. Brown Jr., 2015).

In practice, resilience investments involve either identifying and measuring risk or protecting existing transportation system elements from identified risks. These risks are typically environmental, although other risks, such as to cybersecurity or public health, are sometimes considered. FHWA is partnering on 11 projects that aim to enact resilience through (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 (3) deploying a resilience solution and monitoring performance (U.S. Department of Transportation, Federal Highway Administration, 2018c). Most of these projects involve hardening transportation infrastructure against damages caused by environmental stressors, such as extreme weather events, climate change, or erosion. However, a project by the Utah Department of Transportation instead focuses on measuring and communicating risk information in the form of geographic information system (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 quite rare. 23 C.F.R. § 667, "Asset Management Plans and Periodic Evaluations 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." Reasonable alternatives could include any effort that reduces the need for federal funds, better protects public safety and health, and meets relevant transportation needs (e.g., moving a facility or implementing design changes). The baseline statewide evaluation was due in November 2018. State DOTs must update this overall evaluation every four years and provide any needed updates to roads, highways, or bridges after they are affected by an event (23 C.F.R. § 667.7). Alternate 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 proactive in thinking about system resilience rather than solely focusing on hardening infrastructure. States also are required to develop a risk-based asset management plan for the National Highway System per 23 U.S.C. § 119(e)(1) and MAP-21 § 1106.

Dix et al., 2018, p. 12, identifies "points at which resilience can tie into transportation planning processes." It further notes that "[a]lthough 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 (p. 20). Where performance measures exist, they are often related to flood risk exposure or stormwater management capabilities. The authors also note that "many MPOs have also begun identifying resilience strategies" but often have not performed formal vulnerability analyses or established evaluation criteria (p. 33). In part, this finding could 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 (Pub. L. 100-707 § 311[b] and § 602[a][6]). 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 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 (Pub. L. 115-254, 2018). Under this act, the Building Resilient Infrastructure and Communities program was created, allowing the President to set aside a portion of the Disaster Relief Fund to go toward hazard mitigation (Abbott, Ellard, and Zaltsberg, 2018, Pub. L. 100-707 § 1234).

How Do Transportation Planners Consider Equity?

Many experts note that transportation planning has shifted from a focus on mobility—the ease with which one can move around the transportation system—toward a focus on equity—the ability of the system to provide the opportunity for access to all members of the community. Grengs, Levine, and Shen, 2013, argues that the focus on mobility, using such metrics as travel speed and congestion, was misplaced because these metrics examine the transportation system itself rather than the core outcomes of system users. The authors argue for a shift in focus to access, or 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 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 highlights this shift away from mobility-based transportation planning. They look at the long-range transportation plans (LRTPs) and related documents from 18 large cities in Canada and the United States and argue that transportation planning is shifting from mobility-based thinking to sustainability-based thinking, where sustainability is built on the "3Es" framework (i.e., environment, economics, and equity). They note that this shift is difficult because equity outcomes often are 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 of horizontal equity is a consideration of whether similar neighborhoods have similar access to public transit. Obtaining horizontal equity involves ensuring that similar groups "receive equal shares of resources, bear equal costs, and in other ways [are] treated the same" (p. 4). 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 of vertical equity is a consideration 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 that ability or need might vary across individuals or groups with different incomes, social classes, mobility needs, or abilities. Transportation policies might be regressive or progressive depending on whether they favor certain groups over others. Importantly, Litman points out that these 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 trade-offs between different equity objectives" (p. 4).

How Do Transportation Planners Consider Nontransportation Benefits?

The planning documents of most state DOTs and MPOs suggest that the purpose of resilience investments is to facilitate the safe and efficient movement of people and goods. However, MPOs often cite additional goals, such as achieving environmental objectives or supporting emergency management capabilities. Indeed, 49 C.F.R. § 5303 (a)(1) 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." Similar phrasing is used in other sections of the U.S. Code. Furthermore, 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 such nontransportation benefits as greenhouse gas emission reductions into transportation planning. The 2035 Maryland Transportation Plan includes a goal to "improve the State's emergency management capabilities for natural and man-made disasters by completing emergency management plans and training" (Maryland DOT, 2016).

Several local transportation planning authorities also are responsible for environmental activities and thus have goals that pair transportation planning with environmental stewardship. For example, the Shasta Regional Transportation Agency's 2015 Regional Transportation Plan for Shasta County, California, includes the goal to "practice and promote environmental and natural resource stewardship" (Shasta Regional Transportation Agency, 2015, p. 13). The Chittenden County, Vermont, Regional Planning Commission's Climate Action Guide's first-priority strategy is to "reduce greenhouse gas emissions from transportation/land use" by investing in such emission-reducing transportation options as park and ride facilities, infrastructure for electric vehicle charging, and funding facilities that support bicycles and pedestrians (Chittenden County Regional Planning Commission, 2014, p. 12). The plan also calls for implementing demand-management programs and increasing the availability of public transit. Similarly, the Northeast Ohio Areawide Coordinating Agency, which provides transportation and environmental planning for the greater Cleveland area, issued its AIM Forward 2040 plan, which includes the goal to "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" (Northeast Ohio Areawide Coordinating Agency, 2017). 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" (CH2M HILL, 2014).

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

Who Benefits from Transportation Infrastructure?

Although many 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 improvements can help avoid significant economic losses while addressing equity considerations. For example, there is a shared understanding in transportation planning that infrastructure downtime affects businesses. After a disaster, 40 to 60 percent of small businesses do not reopen (Federal Emergency Management Agency [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 because of disasters. Therefore, transportation investments focus on economic losses that were avoided because of averted transportation disruptions; improved safety through mode changes, which lead to reduced accidents and injury when individuals use the infrastructure; and reduced operational and maintenance costs for the transportation system (American Public Transportation Association, 2016; Burkhardt, Koffman, and Murray, 2003). Other benefits that are less commonly discussed in the literature include those because of targeted investments, such as 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 greenhouse gas emissions (Park and Sener, 2019).

Summary

Overall, the transportation literature appears broadly consistent with the 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” (U.S. Department of Transportation, FHWA, 2014). Much of the literature focuses on disruptions caused by natural disasters, although there are some sources that reflect a broader set of disruption concerns. There is general agreement on the broad intention of resilience, although there is uncertainty about how to best incorporate resilience into the planning process. This is, in part, a measurement challenge. In some cases, planners are uncertain about how to measure resilience. In other cases, planners have access to resilience metrics but are unsure about how to convert metrics into specific and quantifiable policy objectives. The question of how to implement resilience reflects an ongoing change in mindset from focusing on providing citizens with mobility options to providing citizens with access to a system, even when that system faces shocks or stresses.

3. Conceptual Framework

In this chapter, as well as in Chapters 4 and 5, we discuss our conceptual framework, which expands on the 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. We also discuss how that knowledge, when used to make decisions, can lead to a more resilient transportation system and can promote well-being in other socioeconomic systems. This conceptual framework should be reviewed by transportation planners and policymakers for practical planning and decisionmaking considerations in different systems.

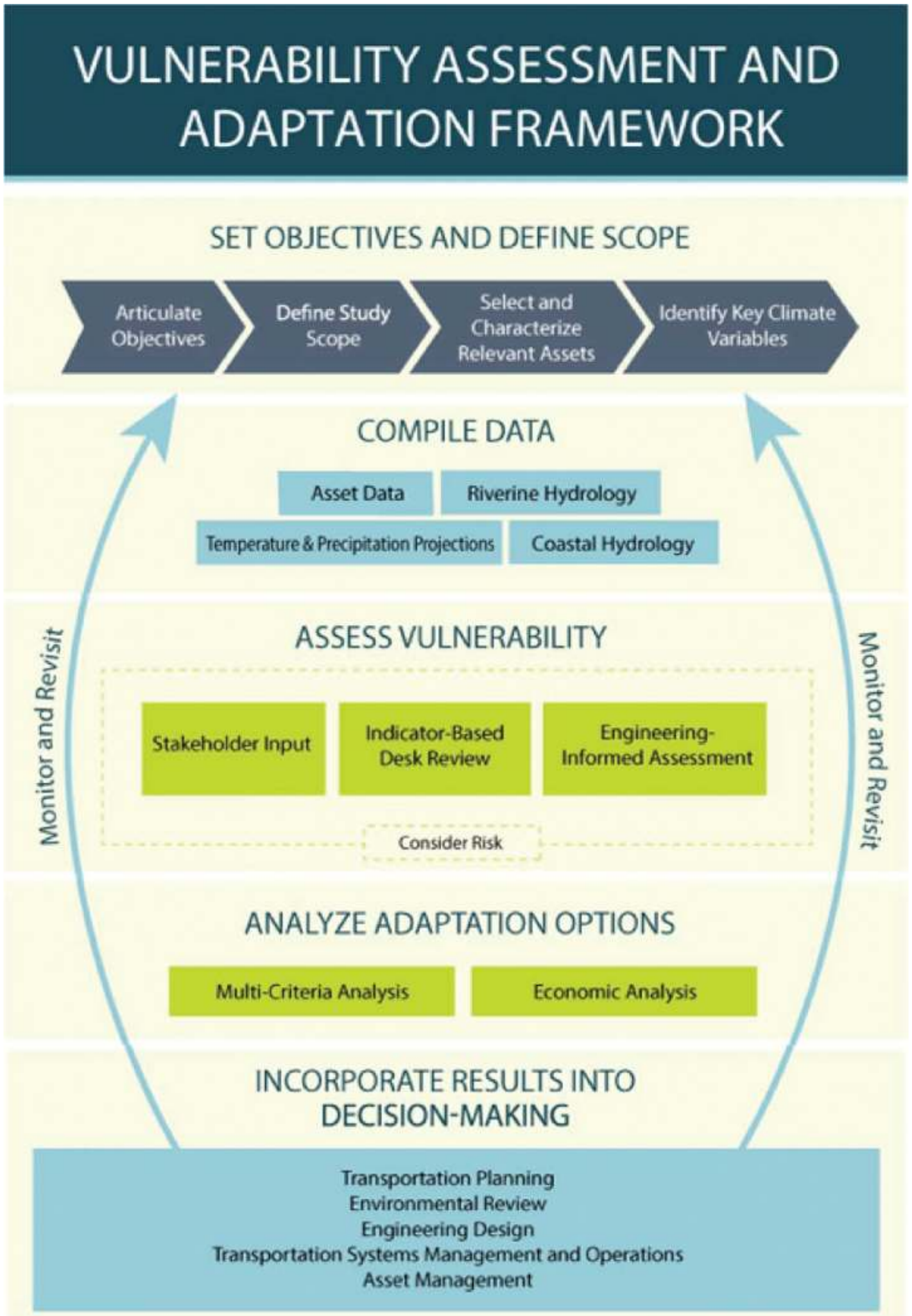
In this chapter and the next two, we discuss our conceptual framework by defining the transportation system and how it fits within a system of systems, list all possible hazards that a transportation system could face, and describe resilience capacities and how they can be used as key levers or devices when deciding what changes to make to the system through targeted investments. We also discuss metrics that can be considered for transportation resilience, and, finally, describe relevant considerations for how this conceptual framework can be applied to MPOs and state-level transportation planning organizations specifically.

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 it is but one system in the system of systems that makes up the larger socioeconomic system. Additionally, transportation is a means to an end and not an end in itself. That is, people use the transportation system to access economically, socially, and environmentally valuable locations. Overlaying these ideas on a more traditional characterization of resilience could contradict 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 incorporate the ideas of resilience into long-term systemwide planning and the decisionmaking process more easily.

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 and vulnerability assessments by highlighting project- and program-level steps that could be taken. It is a resource that provides information on assessment methods to consider, data to use, and what other transportation organizations are doing, specifically focusing on hazards associated with climate change and extreme weather events. We use the VAF as a starting point for incorporating resilience into transportation planning. As illustrated in Figure 3.1, the VAF guides planners in making decisions that might reduce vulnerability.

Figure 3.1. The FHWA VAF



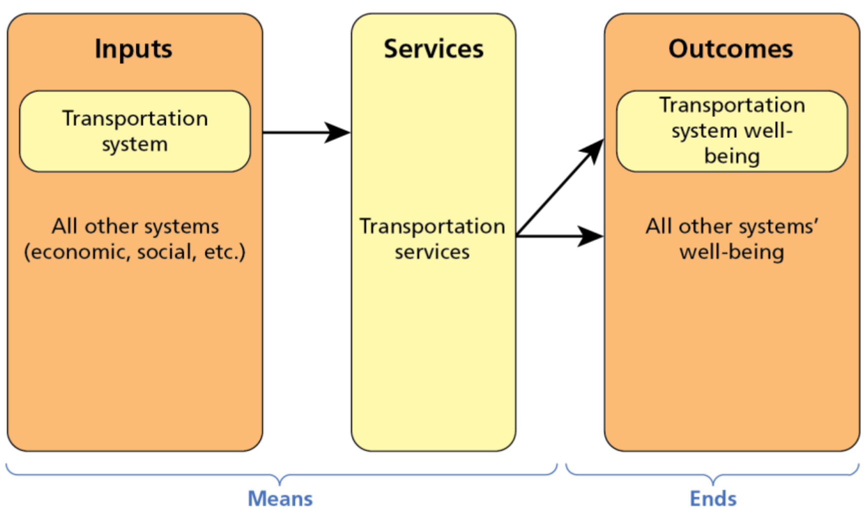
SOURCE: U.S. Department of Transportation, FHWA, 2018a.

By broadly defining the transportation system in a system-of-systems framework, we expand the VAF to allow for a broader set of hazards in order to better incorporate resilience principles. Our approach considers all types of hazards and vulnerabilities to the transportation system, all types of benefits and intended outcomes that a resilient transportation system would provide, and the outcomes in other systems that would result from a more resilient transportation system.

First, based on the findings discussed in the earlier chapters and on information from stakeholders, we define a *resilient transportation system* broadly as one that contributes to the long-term well-being of the community. We use the term *well-being* to describe the continued functioning of the transportation system, which allows the social, economic, and environmental systems to function in an undisrupted fashion. The difference between a resilient and a nonresilient transportation system is that the goal of a typical transportation system is to achieve and maintain business as usual, whereas a resilient transportation system maintains normal functioning both in usual circumstances and 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 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 (e.g., a cyberattack on transportation infrastructure). Importantly, critical elements of the system are exposed to a variety of hazards to which the system must be able to respond using the capacities within it.

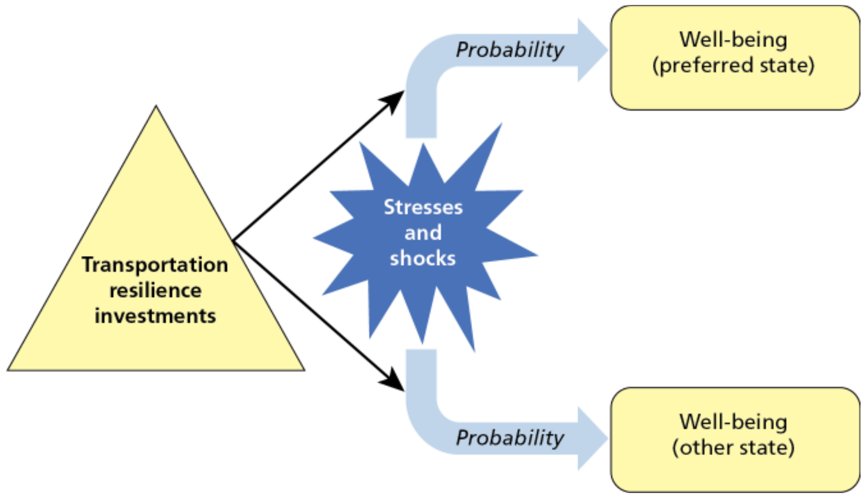
When a resilient transportation system functions appropriately, both in normal circumstances and in times of stress or shock, the social, economic, and environmental systems would continue to operate smoothly. When these systems continue to function, they also continue to produce certain benefits, and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

Figure 3.2. The Transportation System as a Means to Ends



When resilience is considered in this system-of-systems approach, the benefits of prioritized or increased investments in the transportation system likely will increase the probability that the transportation system stays at or near a preferred state of well-being. In this case, we would note that the system is more resilient. This idea is illustrated in Figure 3.3. If one investment provides resilience-enhancing benefits to a stress or a shock, it would create a positive outcome, making the system more resilient and resulting in a preferred state. However, if no targeted investments are made or if the investments are poorly planned, the result might be a less optimal state of well-being.

Figure 3.3. System Well-Being Derived from Changes in the System



How does this concept contribute to understanding what is needed in order 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 that those investments are working? To help answer these questions, we define the main characteristics of the transportation system, the expected hazards the system might face, and the capacities needed to address any stresses or shocks caused by those hazards.

What Is a Resilient Transportation System?

To understand the resilience of the transportation system and to determine how to increase the probability of achieving a preferred state of well-being, we describe what we mean by the transportation system. We provide a conceptual map of the system to discuss the outcomes of the transportation system in particular, 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.

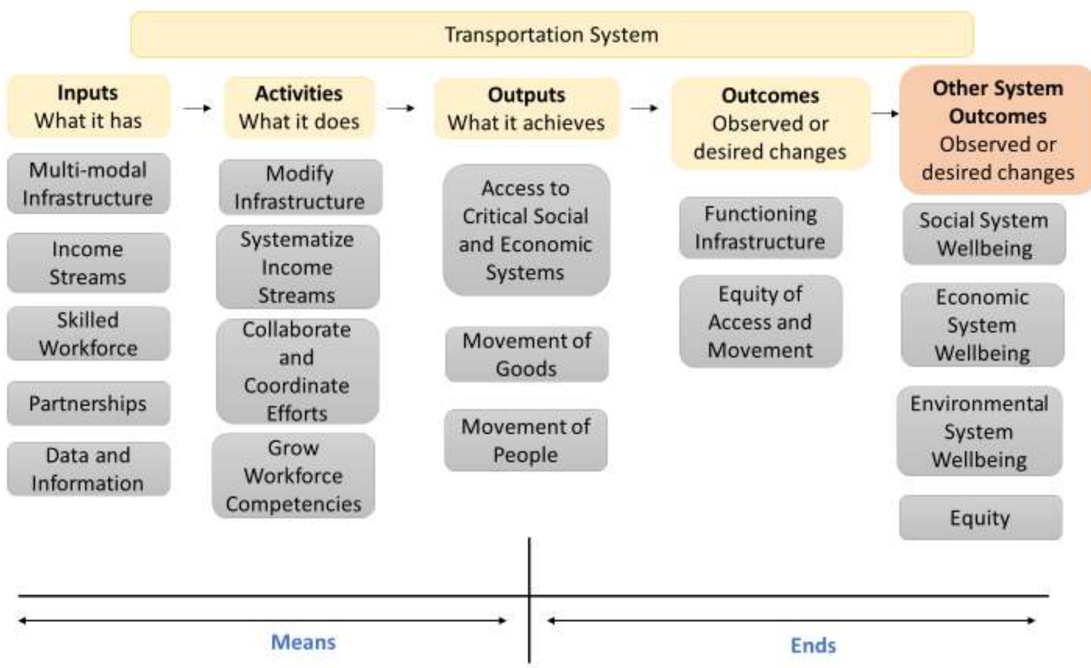
Although we understand that every transportation planning organization has its own structure, our conceptual framework includes certain inputs and actions (i.e., means) that are essential to achieving outputs and outcomes in a more resilient transportation system, as well as in the greater social, economic, and environmental systems (i.e., ends). In Figure 3.4, we show a logic model method for transportation planning organizations to use for decisionmaking.[2] Some transportation planning organizations might be considering such models already. We provide a detailed description

[2] For more examples of logic model use, see footnote 1 in Savitz, Matthews, and Weilant, 2017.

of this conceptual framework, including the main elements of the transportation system that we consider to be linked to achieving greater resilience in a comprehensive system-of-systems approach.

Moving from left to right, Figure 3.4 lists the inputs (i.e., the transportation system's resources), followed by the activities the system conducts with those resources to achieve certain outputs (i.e., the direct results of the activities). These outputs then lead to higher-level outcomes, which are system achievements, including desired or observed changes for the transportation system and in the context of the system of systems. As noted earlier, the left side of the figure shows the means that contribute to the ends found on the right side of the figure. Outputs can be both ends and means that contribute to the broader-level outcomes.

Figure 3.4. Transportation Inputs, Activities, Outputs, and Outcomes



Transportation System Inputs

There are five main types of transportation system inputs. One, which we discuss the most in subsequent chapters, is multimodal infrastructure. Multimodal infrastructure includes a suite of assets, such as highways, local roads, and rail (for drivers and autonomous vehicles), and gray and green infrastructure, such as pathways for pedestrians, bikes, scooters, and powered wheelchairs.

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

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

In addition, it is essential for the transportation system to include formal partnerships with traditional and nontraditional entities and organizations that might influence transportation investments. These partnerships should be characterized by clearly defined missions and collective objectives. Partner entities include public works, port authorities, freight providers, construction companies, chambers of commerce, hospitals and other medical centers, the environmental and social science community, law enforcement, emergency service providers, private-sector building and land developers, energy supply companies, educational institutions, community organizations (e.g., faith-based organizations, community centers), advocacy and lobbying groups, and government officials. The ease of these partnerships might be influenced by different business models. For example, the partnerships might be easier for MPOs that are hosted by other agencies than for independent MPOs. According to Kramer, Carroll, and Karimi, 2017, hosted MPOs allow for enhanced coordination, more financial assistance, and lower operational costs. However, they can face greater challenges of autonomy in decisionmaking. These points are imperative when considering the transportation system as one in the broader system of systems.

Finally, the system should have relevant, useable data and information on critical aspects of the transportation system, such as congestion, network chokepoints, infrastructure assets, roads, bridges, and tunnels that are vulnerable to risk. Information on the social system also is needed, including on education; health services; and economic systems, such as businesses, in order to understand the criticality and user base for different transportation system components.

Transportation System Activities

Four main activities or actions can be employed to achieve certain outputs in a functioning transportation system. One such activity is targeted and prioritized changes to the transportation infrastructure with consideration for land use and private-sector actions, as well as their impacts on the transportation infrastructure. These modifications can include hardening and adapting infrastructure (e.g., adding, moving, or raising roads; 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 can increase its competencies through training and professional development. The skilled workforce can assess the available funding streams to determine where changes would be best targeted. For example, funding might need to be diverted to increase the resilience of particular infrastructure assets to specific risks. By investing in the skills of people within the system, the workforce can ensure business as usual and aid in planning and executing responses to stresses and shocks.

Collaboration and coordination among partners can result in better targeting of aspects of resilience through funding streams and changes to the multimodal infrastructure, especially where there is jurisdictional overlap. Collaboration and coordination can be done well when the transportation system and its partners have mutual goals and outcomes.

Increased diversity in partnerships can help parties understand what nontraditional partners might change in the planning and decisionmaking processes 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 could coordinate about land use through discussions and information sharing with a transportation partner to ensure continued mobility on that road. Including such considerations as hydrologic factors, knowledge of floodplains and water runoff, and drainage can ensure that a roadway is not flooded after rainfall, which would decrease the possibility for congestion. As discussed earlier, those who benefit from the transportation system can be informed by the transportation planning workforce and relevant partners about important stresses, such as closed roads or other critical factors that can affect access to and movement within the transportation system.

Transportation System Outputs

In an ideal system, the inputs and activities will achieve three main outputs. The first output is access to critical social and economic systems. The transportation infrastructure provides access to critical nodes or destinations within the network in a given geographic location. Those nodes lead to jobs; childcare; health care; education; leisure activities; law enforcement; social networks; and social support communities, such as families and friends. Access to desired destinations, or "physical access to places," is provided through different modes and alternate routes of the multimodal system (Governors' Institute on Community Design, 2017).

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

Finally, the transportation infrastructure provides users with safe, flowing mobility (absent congestion) to and from desired destinations.

Transportation System Outcomes

The outputs from transportation system activities lead to two main outcomes in a resilient transportation system. The first 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 of Figure 3.4 (inputs, activities, and outputs) succeed at maintaining normal functioning in a given geographic area of responsibility. In addition, even in the face of a stress or shock, levers (e.g., choices, actions, and capacities) are in place that allow the transportation system to function normally, with minimal interruptions. Each input, activity, and output can provide different benefits. For example, as Burkhardt, Koffman, and Murray, 2003, notes, coordination with partners might result in more-visible, higher-quality transportation services; enhanced mobility; and more funding sources and cost-saving opportunities.

The other main outcome of the transportation system is *equity*, access to movement for all individuals, including the socially vulnerable or economically disadvantaged; those in low-income areas; and those with special needs, such as young children, the elderly, and those with certain medical conditions. We recognize that the term *equity* can have many different definitions. Manaugh and colleagues (2015), which refers to this concept as *social equity in the transportation system*, reviewed the goals, objectives, and related measures of several transportation plans. The goals identified often encompassed such ideas as "better access for all," "increase[d] transportation alternatives," and "accessibility and mobility for all." We thus treat equity as an outcome of achieved access and mobility, where options are available to the socially vulnerable; those who are geographically distant from transportation infrastructure; and those who lacked options with affordable fees for service for public transit and community-led ride sharing services, or personal vehicles. 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 shows that in a resilient transportation system, transportation outcomes have direct relationships with social, economic, and environmental system well-being in the given geographic area. The means, as illustrated in Figure 3.4, are the activities—i.e., transportation system services (movement of goods). The outputs can represent both the means and the ends. The outcomes—i.e., a functioning transportation system—contribute to the ends that all other systems (social, economic, and environmental) continue functioning. In the social system, desired outcomes include the ability of individuals to access and move safely to destinations where they can interact with their social networks or receive needed services at medical centers, education institutions, and libraries; shopping areas for essential and nonessential items; and areas that contribute to wellness, such as parks and green spaces. For the economic system, outcomes include the ability of businesses and governments to continue providing services, people having access to their jobs, and transportation systems ensuring that goods reach their destinations. For the environmental system, the outcome of interest—well-being—is achieved when the transportation infrastructure does not disrupt natural processes, such as the direction of water runoff, facilitates the protection of certain ecosystems (e.g., wetlands), and limits the possibilities for erosion or flooding. Other related outcomes would include increased use of greenways, pedestrian modes, and public transit, which can enhance air quality by reducing greenhouse gas emissions and pollution (Ngo, Frank, and Bigazzi, 2018). Another related outcome is the use of environmentally friendly construction materials or such devices as flow-through planters.

Equity can be achieved in systems that are able to continue functioning. 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 and Russell, 2016).

We acknowledge that not all of the elements in Figure 3.4 might be new ideas for transportation planners. We wish to present a new way of thinking in which each element is leveraged in a way that might differ from how these resources are currently used and therefore contribute to more-resilient transportation system ends. Next, we will briefly discuss the possible hazards to transportation systems and the aspects of resilience that can be used to achieve well-being (Figure 3.3). Specifically, we 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 also must be aware of the hazards that are most likely to cause stress or shock in their geographic areas. Using stakeholder discussions and the literature review, we summarize the hazards that transportation systems could face in Table 3.1. In this table, we list additional hazards that are 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–related and extreme weather events	Avalanche
	Drought
	Earthquake
	Erosion
	Extreme heat
	High wind
	Increased precipitation (e.g., rain, snow, ice)
	Landslide
	Hurricanes
	Tornados
	Rockfall
	Sea level rise
	Storm surge
	Temperature fluctuation
	Wildfire
Human-induced hazards	Adverse actor physical threat
	Autonomous vehicles
	Congestion
	Cyberattack
	Driver error
	Population growth
	Toxic or flammable substance exposure

Planners must try to improve the resilience of transportation investments to the most likely hazards in their areas. Targeting efforts has the potential to reduce significantly the impacts of shocks that result from these hazards. Transportation planners also focus on some hazards that are unavoidable, such as the impacts from climate change or an extreme weather event. However, some hazards—such as congestion, cyberattacks, or physical attacks on the infrastructure by adverse actors—might be avoided or their impacts reduced with a thorough understanding of particular elements of the transportation system and how investments in those elements can play a role in hazard avoidance (see Figure 3.4). As Zimmerman and Dinning, 2017, p. 18, notes, if cyberattacks are not averted, "[s]ocial 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 the transportation system are important to consider because the transportation system is a means rather than an end in the larger socioeconomic system.

We now shift our focus to other capacities that can help the system achieve greater resilience and therefore greater well-being.

Understanding Aspects of Resilience

As discussed in Chapter 2 and in Appendix B, Bruneau and colleagues' 2003 framework defines a resilient system as having the following characteristics:

- reflective: continuously evolving
- robust: anticipating potential failures
- redundant: having spare capacity to accommodate disruption
- flexible: the system is able to change, evolve, and adapt
- resourceful: alternative approaches are available
- inclusive: incorporating equity and community response
- integrated: alignment across the system.

It might be difficult to think of these seven characteristics in a transportation context. For example, the concept of a reflective transportation system might not make sense. Although transportation infrastructure is changing, the transportation itself is not evolving; it is absorbing and adapting to changes. Therefore, we map some of the characteristics from Bruneau and colleagues' 2003 framework to capacities that could be more applicable to the needs of transportation planners. We call this the AREA approach to resilience: AREA stands for

- absorptive capacity
- restorative capacity
- equitable access
- adaptive capacity.

When we say *absorptive capacity*, we are referring to the ability of the system to absorb shocks and stresses and maintain normal functioning. *Restorative capacity* is the ability of the system to recover quickly following a shock or stress and return to normal functioning. *Equitable access* is the ability of the system to provide 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 attempting to increase the resilience of the transportation system. That is, it might be more cost-effective to invest in adaptive or restorative capacity than absorptive capacity to maintain system functioning in normal and disrupted times. For equitable access, there might not be a substitute for the other three.

To put these capacities into perspective for the transportation planner, we provide a few examples. Investments in absorptive capacity could be investments in hardening the transportation infrastructure, such as building a floodwall to reduce the probability that a road is flooded or making more green infrastructure investments that change the drainage pattern around roads. Investments in restorative capacity could be investments in equipment, crews, and partnerships with different income streams so that the infrastructure is repaired more quickly following an event. Investments in equitable access could include increasing transit service, for example, by increasing the number or frequency of bus lines across the community or by providing multimodal access to vulnerable and remote populations. Adaptive capacity investments could include adding roads that provide redundancy so that the system can handle more traffic, reducing potential congestion during both disrupted and normal conditions. Each of these capacities provides alternative means to achieving the end of a resilient transportation system. The capacities also are context-dependent. There are different communities 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.

We have discussed these capacities at a systems level, but because the transportation system is inherently a network, the AREA approach could be applied to subsystems in the transportation system or to the assets themselves. Understanding the networked nature of the transportation system and how these capacities might be realized is paramount to identifying strategies for long-term investment going forward. The Colorado DOT study discussed in Chapter 2 provides a starting point for considerations of the criticality of different components of a transportation system and how these components are exposed to multiple hazards to varying degrees (see Figure 2.1 in Chapter 2). In the next section, we expand on the idea of criticality.

Recasting Resilience in a Network Context

As discussed earlier, many resilience frameworks are embedded in a system-of-systems framework. What makes the transportation system different from most other systems is the network context that underlies the entire system. Therefore, there are systemwide considerations of resilience along with considerations of the resilience of assets in 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 discuss resilience without mentioning two important aspects of criticality and exposure. Resilience is not only the vulnerability of the system to a suite of hazards but also how disruptions in one area of the network can cascade or spill over to other areas of the network. Thus, it is important to better understand the criticality of different assets of the transportation system.

For Colorado DOT (Flannery, Pena, and Manns, 2018), a measure of criticality was constructed using metrics of traffic flow, asset capacity, and proxies for the value of goods and services flowing on the roadway. However, criticality also includes metrics of social vulnerability for the population surrounding 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 few alternate routes are considered critical according to the Colorado DOT criticality index. In essence, *criticality* is how important a segment is to the movement of goods and people, while providing access to vulnerable populations. This is consistent with the definition of criticality used in other contexts (see, for example, U.S. Department of Transportation, 2014).

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 is disrupted, cascading effects in the network cause further disruptions to take place. The criticality and exposure of these assets to the suite of hazards determine the resilience of the system. That is, a resilient transportation system is one in which critical assets are not exposed to hazards or, if they are, there is sufficient absorptive capacity, adaptive capacity, restorative capacity, or equitable access to mitigate the impacts of a shock. It is important that criticality and exposure are considered together when planning for a more resilient transportation system.

For example, consider the system illustrated in Figure 3.5 and described in Table 3.2 in terms of which assets linking different nodes are critical and at risk of exposure to a stress or a shock. In this system, the most critical node is where the hospital is located. In this case, it might be that assets (i.e., transportation infrastructure) 1, 3, 5, and 6 are critical to the system functioning because of their connection to the hospital. However, because there is considerable redundancy (additional or alternate routes) through assets 2 and 4, the criticality of assets 1, 3, and 5 is reduced. Suppose that assets 3, 4, and 6 are exposed to hazards. This suggests that the absorptive, adaptative, and restorative capacities of asset 3 should be expanded to increase the resilience of the system. However, the resilience of asset 6 could be expanded by adding an additional route (redundancy) to connect it to the rest of the network rather than by hardening or increasing its absorptive capacity. This further suggests that the equitable access of asset 6 might need to be considered because the opportunity for access to the hospital is easily denied for those located along asset 6.

Figure 3.5. Conceptual Network Infrastructure and System Nodes

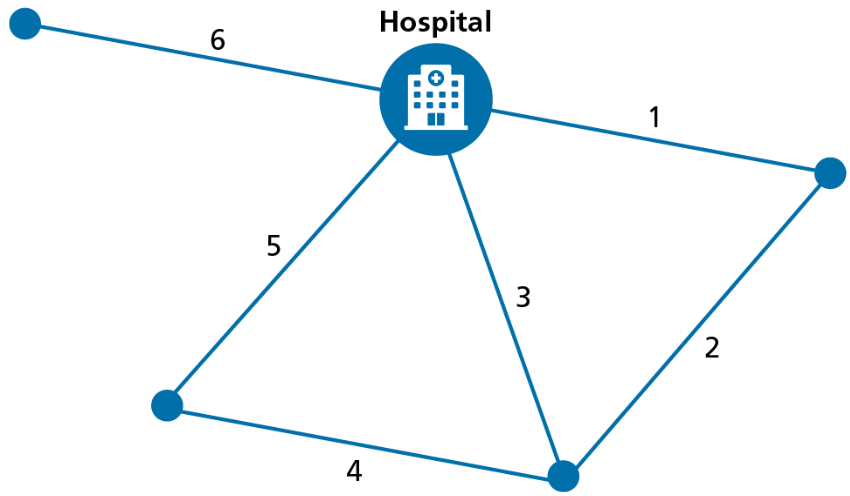


Table 3.2. Conceptual Network Infrastructure Criticality and Exposure Mapping

Asset	Criticality	Exposure
1	Yes	No
2	No	No
3	Yes	Yes
4	No	Yes
5	Yes	No
6	Yes	Yes

Importantly, in this context, we are using the AREA approach, employing the known criticality and exposure of the network to consider where future investments might need to be made. This allows us to explore how alternative investments to reduce criticality and exposure can be made to increase the resilience of the system rather than focusing on hardening the system. Additionally, the criticality of different assets and how they are distributed across the community provides a means for understanding equitable access to the transportation system. Long-term transportation planning should consider the suite of available options for investment by using the AREA approach to resilience to reduce criticality and exposure across the system. Doing so will improve the functioning of the system in both normal and disrupted times, increasing the probability of transportation system well-being, as illustrated in Figure 3.3. The benefits that accrue during normal operations could outweigh the benefits that occur only during times of stresses and shocks. Thus, by choosing among the suite of potential projects consistent with the AREA approach, cost-effective improvements can be made that improve the overall functioning and resilience of the transportation system.

Summary

In this chapter, we discussed a conceptual framing of the transportation system, including the elements of the system, possible hazards to that system, and capacities that can be considered when making changes to critical parts of the system to achieve greater resilience. Using the AREA approach to resilience could provide transportation planners with a way that allows for greater transparency in developing and choosing alternative investment strategies for long-term planning. This conceptual logic model framing and the AREA approach will help guide the implementation of the FHWA VAF, including an emphasis on resilience to a set of hazards that are not necessarily associated with climate change.

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

4. Measuring Resilience

As we explained in the AREA approach in the previous chapter, resilience is a multifaceted concept: 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 variety of metrics to assess and understand the impacts of the investments they make through AREA to improve the resilience of the assets in the transportation system. In this chapter, we provide guidance on how to measure the resilience of transportation systems by presenting a variety of quantitative and qualitative metrics that can be used to measure the distinct system capacities discussed in the AREA approach. We also consider the elements of the system that contribute to reduced exposure to all types of hazards, either natural or human-induced.

Metrics for Resilience

It is important to remember that resilience is an abstract concept but is expected to result in the tangible outcomes listed in Chapter 3. Assessing resilience first requires 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, transportation planners in the northeastern United States might want a resilient system that continues to function and enable all users to reach their desired locations with minimal delay during a snowstorm that drops up to six inches of snow over the course of four hours. A system that can maintain functioning during a particular stress or shock is considered resilient. As discussed earlier, this requires planners to identify the shocks and stresses to which the system should be resilient. The statement in the literature and stakeholder interviews that the transportation system should be resilient usually means 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, the system should be referred to as resilient to the desired suite of shocks.

Impacts of hazards and the stresses or shocks they produce can be reduced through considering AREA 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 their systems more resilient to a wider variety of relevant shocks and stresses.

Metrics in general help transportation planners inform plans, decisions, and assessments to understand whether their systems will meet a desired level of resilience when faced with a variety of stresses and shocks (Savitz, Matthews, and Weilant, 2017, pp. ix, 1). 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 systems (Yee and Niemeier, 1996). Determining which metrics are most important to use or improve depends on the type of stress or shock and the level and type of service or part of the transportation system planners are trying to maintain. For example, increasing the availability of alternate routes or alternative mode choices might be the best choice for increasing resilience against certain types of shocks, while improving the reliability of major thoroughfares could improve resilience against other types of stresses or shocks. Identifying the appropriate metric requires planners to consider the needs and context of each network and individual subsystem setting, as well as the goals of the planning organization. Therefore, in this chapter, we present a variety of metrics that transportation planners can consider applying to their own transportation systems.

These metrics can be useful for tracking progress in achieving resilience for different elements of the transportation system (see Figure 3.4 in Chapter 3). Metrics based on existing or desired data and information can be mapped to each element of the logic model to help planners clarify what they are measuring and identify gaps in measurement that might exist. Broadly, metrics for inputs track the resources that currently make up the transportation system and the status of those resources. Metrics for activities track the actions being taken in the transportation system. Metrics for outputs measure the performance of the transportation system itself and might be directly altered through changes in activities. Metrics for outcomes measure the transportation-related experiences of system users. In some cases, transportation planners might want to measure outcomes in other social, economic, and environmental systems that result from transportation services, such as economic development or jobs by location.

Measuring Resilience at Each Step of the Transportation Framework

In the remainder of this chapter, we provide examples of metrics that correspond to each step of the logic model discussed in Chapter 3. We categorize metrics for inputs and activities according to the capacity to which each metric corresponds. We then discuss metrics related to outputs and outcomes. In Table 4.1, we show how categories of metrics map to relevant steps of the transportation system logic model and AREA capacities described in Chapter 3. Specific metrics in each category are discussed further in the body of the report. A single metric might map to different steps of the logic model or to multiple AREA capacities.

Table 4.1. Metrics for Measuring AREA Capacities

Step of Logic Model	AREA Category	Categories of Metrics
Inputs	Absorptive capacity	Exposure metrics
	Restorative capacity	Available response resources
	Equitable access	Availability of public transit; availability of alternative mode choices
	Adaptive capacity	Availability of alternate routes and alternative mode choices
Activities	Absorptive capacity	Maintenance metrics
	Restorative capacity	Measures of community planning efforts; measures of communities' communication capabilities
	Equitable access	Measures of communities' communication capabilities
	Adaptive capacity	Network expansion
Outputs	N/A	Intensity of route use or vehicle miles traveled (VMT); measures of the 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

Our descriptions of specific metrics are not exhaustive: We do not provide a comprehensive list of the metrics planners should consider. Rather, we provide exemplary metrics 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 of those documented in Chapter 2 and new metrics for consideration.

Measuring Inputs and Activities

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

Absorptive Capacity

As noted earlier, *absorptive capacity* is the ability of the transportation system to absorb shocks and stresses and maintain normal functioning. This capacity can be increased by hardening assets or reducing exposure to risk. In the literature, absorptive capacity in transportation is an understood approach to resilience, although it is not necessarily labeled in such a way. Therefore, there is a wide variety of metrics available to understand what a given transportation system's absorptive capacity is. Most of the discussion of this capacity addresses the multimodal transportation infrastructure element of the logic model in Figure 3.4 in Chapter 3.

Inputs for absorptive capacity involve understanding the exposure of the transportation system infrastructure to shocks and stresses, and a discussion of such metrics can be found in Dix et al., 2018. Examples include the mileage of transportation assets in high-risk areas for such natural hazards as floods, wildfires, or landslides. Exposure to risks beyond natural hazards, such as cyber risk, fleet changes, or policy changes, also should be considered. In addition to the transportation assets, measures of the number of destinations (including such critical assets as hospitals; energy production, transmission, or distribution facilities; and schools) that are exposed to risk can be useful. In some cases, planners might be able to measure the extent to which the transportation infrastructure can absorb shocks or stresses without a loss of performance: for example, 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 also should consider the return periods of risks that are most relevant to their regions.

Transportation planners frequently invest in activities to increase the absorptive capacity of their systems. Examples of such measures include the annual percentage of routine inspections or maintenance activities completed on time for all assets or the number of weatherization repairs made each year. Some metrics track preventative care and planning pre-stress or pre-shock, such as the monthly amount of litter or debris removed from storm drains, culverts, or roadsides or the number of projects that raise the roadway grade. Similarly, metrics can track the number of stormwater management improvements through, for example, a watershed basin's ability to maintain service and absorb rainfall in a given area over a certain period of time (see Hillsborough County Board of County Commissioners, 2008). There also might be investments in training emergency response personnel or in communication technology that would alert users to changes in system conditions or availability (see Table 4.2).

Table 4.2. Sample Metrics for Absorptive Capacity Inputs and 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) Percentage of facilities that accommodate two feet of sea level rise
Activities	Maintenance metrics	Annual percentage of routine culvert inspections completed on time Quantity of litter or debris cleared from storm drains, culverts, and roadsides (reduce roadway flooding) Number of stormwater improvements Number of projects that raise the roadway grade or increase resilience against climate change or natural disasters though other means

SOURCE: Data are from Dix et al., 2018.

Restorative Capacity

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

Inputs for restorative capacity measure existing capabilities to respond to shocks and stresses, including measures of personnel and partnerships, such as counts of construction equipment and workers in the region. Inputs also include budgets—particularly discretionary income available during emergencies—and physical resources 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 users also should be aware of and involved in the planning process. Measures of community efforts can help planners understand how 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 grassroots nongovernmental body for planning disaster risk–reduction interventions and postevent responses, the frequency of community organization meetings, attendance at these meetings, and the percentage of communities or neighborhoods with community bodies that have clearly defined and supported roles in the response process. Although grassroots organizations might be unable to replace the services provided by official organizations, their involvement could improve community engagement with postevent 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 it can be quickly and effectively communicated to all users of the transportation system. Metrics that measure communication capabilities include the amount 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 in a given number of hours following an event, the percentage of employers that pass reliance communications to employees, and the number of modes of engagement for reaching community residents. These communication capabilities can serve roles that include transportation, such as communicating what routes are open or closed during evacuations or how public transit is responding to severe weather disruptions (see Table 4.3).

Table 4.3. Sample Metrics for Restorative Capacity Inputs and Activities

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 or neighborhoods with at least one grassroots nongovernmental body for planning disaster risk–reduction interventions and postevent responses. Frequency of community organization meetings
		Attendance at community organization meetings (number of people) Percentage of communities or neighborhoods with community bodies that have clearly defined and supported roles in disasters
	Measures of communities' communication capabilities	Amount 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 Percentage of employers that pass resilience communications to employees Number of modes of engagement for reaching community residents

SOURCE: Data are from 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 involves the availability of alternate routes and alternative mode choices. These metrics can help planners understand the inputs that make up the transportation system and how well the system can continue to operate when segments of the network are closed, for example, for repair and maintenance. Measures of the availability of alternate route choices include the distance to alternate routes, the number of reliable routes, and measures of network density (e.g., block lengths or street miles per square mile). Discussions of alternate 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, developed a metric called *friability*, or 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 percentage of low-income-household income that goes toward transportation costs, the amount 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 nonmotorized modes of transportation, and the percentage of travelers that use particular forms of transportation. Discussions 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, include tracking the percentage of planned additional mileage completed and the number of alternative mode projects implemented (see Table 4.4).

Table 4.4. Sample Metrics for Adaptive Capacity Inputs and Activities

Step of Logic Model	Category	Sample Metrics
Inputs	Availability of alternate routes and alternative mode choices	The distance to alternative routes
		Friability, or the change in the population-weighted average number of passable routes connecting nodes in a network following a disaster
		The number of reliable routes
		Network density (block lengths; street miles per square mile)
		Ratio of percentage of transportation funding received by mode to the percentage usage of mode
		The portion of low-income-household income going toward transportation costs
		Physical separation between traffic and pedestrians or cyclists
		Measures of mode split
		Multimodal door-to-door travel time
		Car ownership rates
		Percentage of street miles with nonmotorized facilities
Activities	Network expansion	Percentage of planned nonmotorized facility miles completed
		Miles of planned nonmotorized facilities built

SOURCES: Data are from 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.

Equitable Access

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 when the system is undisrupted. Equity is concerned with the transportation system itself as well as the ability of different populations to access the transportation system.

Measures of the availability of public transit include the percentage of a region's population living and working within proximity to transit stops. This metric might be tailored to specific populations, such as low-income households living within one-half of a mile of a high-frequency public transit service. Such equity metrics also concern the underlying population distribution across the region, including the distribution of vulnerable populations. Discussions 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 toward 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 of 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 different access to the transportation system during times of shock or stress. Such metrics as heat vulnerability indexes, as described in Madrigano et al., 2015, can highlight where groups are located to determine where access limitations might occur.

Communities' communication capabilities are measures of both restorative capacity and equitable access. Rapid and effective communication of key information is important to restoring the functioning of the transportation system and to ensuring that all users understand how to access and use the transportation system. For example, sensitive populations that rely on public transit need to know whether there are changes in the operation of that system during weather emergencies. At the same time, those sensitive populations might have access to fewer sources of information about the status of the system (see Table 4.5).

Table 4.5. Sample Metrics for Equitable Access Inputs and Activities

Step of Logic Model	Category	Sample Metrics
Inputs	Availability of public transit	Percentage of the region's population living and working in proximity to transit stops
		Percentage of the total population in a given area, including vulnerable populations served
		Number of low-income households within one-half mile of high-frequency transit service
	Availability of alternative mode choices	The portion of low-income-household income going toward transportation costs
		Physical separation between traffic and pedestrians or cyclists
		Measures of mode split
		Multimodal door-to-door travel time
		Car ownership rates
		Percentage of street miles with nonmotorized facilities
Activities	Measures of communities' communication capabilities	Amount 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
		Percentage of employers that pass resilience communications to employees
		Number of modes of engagement for reaching community residents

SOURCES: Data are from 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 to improve the well-being of transportation system users. The direct implications of these activities are measured as *outputs*, or changes that occur in the transportation system as a result of the activities. These outputs are important because they result in *outcomes*, or 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 different times. Discussions 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 system infrastructure or because of a shock. Some metrics might be specific to a road, route, or mode choice, such as 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 of the route. Transportation planners might 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 planners a sense of the adaptive capacity of the system (see Table 4.6).

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

Measures of the state of repair of a transportation system can be important for understanding how easily a hazard or normal wear and tear might result in significant reductions in service capacity. If the road conditions are not good and if a route could be washed out or eroded during a shock, access to destinations and movement of goods and people might be reduced. These types of measures can include metrics of road surface conditions, such as the International Roughness Index. There are metrics for the condition of bridges, sidewalks, crosswalks, and bicycle infrastructure. These metrics help planners understand the results of current system services and what the infrastructure can absorb in terms of demand. Such metrics, combined with a given road's closure time within the network, will help planners understand how well the remaining routes can absorb the traffic flow. We discuss the continued functioning of the transportation system in a time of stress in the next section.

Table 4.6. Sample Metrics for Outputs

Step of Logic Model	Category	Sample Metrics
Outputs	Intensity of route use or VMT	Number of people traveling along or through route each day
		Number of hours people spend traveling along or through route each day
		Worker inflow and outflow
		Traffic volume or capacity ratio
		Number of public transit riders
	Measures of a transportation system's state of repair	International Roughness Index
		The percentage of roadways in poor or fair condition
		Pavement and bridge condition on the interstate system and on the remainder of the national highway system
		Pavement and bridge condition on local roads
		Condition and availability of sidewalks, crosswalks, and bicycle infrastructure
	Reliability metrics	Measures of resilience (Zhang et al., 2010)
		Truck Travel Time Reliability (TTTR) Index
		Vehicle delay

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

Outcomes

Metrics of congestion, travel time, and travel speed help measure how efficiently the transportation system moves users between locations under normal and restricted conditions. Discussions 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 can 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 indexes, 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.

One method decisionmakers could consider is to use longitudinal data, which 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) developed a framework for calculating MORs. It defines a 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 identify reliability because they 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 return to normal operating levels as quickly as possible.

There are multiple 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 in a given number of minutes. Like many metrics, these can be calculated for the population at large or for specific subgroups. There are not standard values for the parameters. 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 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 by discounting opportunities that take longer to reach or are further away. Discussions of cumulative opportunity metrics and gravity measures can be found in Geurs and van Wee, 2004; Fan, Guthrie, and Levinson, 2012; Venter, 2016; and Governors' Institute on Community Design, 2017. Another example of an access metric is the prevalence of walkability score metrics, which assess how many desirable destinations are within a walkable distance of a given location. Such metrics are popular and prevalent on sites that help individuals search for housing options. There also are utility-based accessibility measures that are derived directly from discrete choice models. Discussions of walkability scores and discrete choice methods can be found in Venter, 2016; Governors' Institute on Community Design, 2017; and Twaddell et al., 2018. Furthermore, the University of Minnesota's Accessibility Observatory hosts a variety of data and research on different accessibility metrics across different U.S. cities (University of Minnesota, undated). See Table 4.7 for some sample metrics for outcomes.

Table 4.7. Sample Metrics for Outcomes

Step of Logic Model	Category	Sample Metrics
Outcomes	Measures of congestion, travel time, and travel speed	Car or truck speeds and car or truck counts, e.g., how much time passed from 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, which is a qualitative measure expressing the quality of transport service from the point of view of the user and is largely 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)
		TTTR Index
		Vehicle delay
	Accessibility metrics	Number of destinations within walking or biking distance
		Walkability score–style metrics
		Utility-based accessibility measures derived directly from random utility discrete choice models

SOURCES: Data are from Adams, Bekkem, and Toledo-Durán, 2012; Governors' Institute on Community Design, 2017; Flannery, Pena, and Manns, 2018; Venter, 2016; Ewing, 1993; Hoogendoorn-Lanser, Schaap, and van der Waard, 2012; National Research Council, 2002; Tennessee Department of Transportation, 2015; Parkany and Ogunye, 2016; Tierney and Bruneau, 2017; Zhang et al., 2010; Jenelius, Petersen, and Mattsson, 2006; Chen and 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, which help measure the investments in AREA, there are several other metrics that help transportation planners assess the impacts of the entire system. Savitz, Matthews, and Weilant, 2017, p. 16, notes that "Reasoned analyses about why the values of measures are changing, or how they are likely to change if policies shift, need to take into account 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 remain 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 might value the benefits of the system beyond the costs of using or having access to the system. Housing prices and other costs might increase in proximity to highly desirable transportation systems as individuals pay premiums to obtain easy access to the transportation system. This can create equity challenges because low-income individuals who transportation systems often are intended to serve might 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. Given this problem, it is important to measure the cost of transportation and cost of living for system users, particularly vulnerable or low-income populations. Such metrics include measures of housing costs, single-mode or multimodal transportation costs, and the change in travel costs associated with a shock or stress. Discussions 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

Resilience is an abstract approach to thinking about how a system of systems responds to different shocks and stresses. The FHWA VAF can be broadened by taking the AREA approach for resilience and using it to replace vulnerability in the overall framework.

We make the following recommendations for implementing the VAF in order to incorporate more aspects of resilience:

- Expand the objectives and scope of the framework to include shocks and stresses that are not directly tied to climate change, including cyberattacks.
- Broaden the asset data to include human and equipment assets, use the logic model to guide expansions, and identify the criticality of these new assets.
- Expand hazard data to consider a wider array of hazards, including cyberattacks, and determine whether they are systemwide or if they influence only a subset of assets.
- Use the indicators we identified to assess the resilience of the system in a way that acknowledges the interaction of the criticality and exposure of the assets.
- Engage stakeholders and decisionmakers to help weigh the trade-offs that come with prioritizing options.
- Use an established critique, such as multicriteria decision analysis, economic analysis, benefit-cost analysis, or life cycle cost analysis, to facilitate prioritization.
- Consider the benefits of investment in times of both normalcy and disruption.

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 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 the 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 decisionmaking.

Articulating Objectives and Defining the Study Scope

In this step, the goals and boundaries of the study are defined. The scope and scale of an assessment is bounded by the assets the organization has control over and the characteristics of those assets. In addition to the assets, it is important to define the hazards that will be considered as part of the vulnerability assessment. The VAF is designed to consider climate change vulnerability but it can be expanded to consider shocks and stresses that are not directly tied to climate change. In particular, the inclusion of human-induced disruptions, such as cyberattacks, can be incorporated into the scope of the study, although assessing the risk of cyberattacks might be less straightforward than assessing the risk of flooding where inundation maps exist. As we discussed in Chapter 3, a broader set of hazards should be incorporated into the scope of resilience. In Table 5.1 (which is the same as Table 3.1), we provide 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–related and extreme weather events	Avalanche
	Drought
	Earthquake
	Erosion
	Extreme heat
	High wind
	Increased precipitation (e.g., rain, snow, ice)
	Landslide
	Hurricanes
	Tornados
	Rockfall
	Sea level rise
	Storm surge
	Temperature fluctuation
	Wildfire
Human-induced hazards	Adverse actor physical threat
	Autonomous vehicles
	Congestion
	Cyberattack
	Driver error
	Population growth
	Toxic or flammable substance exposure

Obtaining Asset Data

Once the scope of the vulnerability study is known, obtaining information about the assets is the next step. As FHWA suggests, this could be the suite of commonly considered attributes used to identify capacities and use of assets and geospatial data regarding location in interconnectedness of the network. Having a clear understanding of the entire system is important for any long-term planning study. Knowing how assets form transportation outputs and socioeconomic outcomes is important in order to understand how the system should be modified in the future. According to our logic model, which we described in Chapter 3, the inputs to the transportation system are not only physical assets but also the human and equipment aspects that can be used to alter the impact of disruptions because of shocks and stresses. Incorporating these broader sets of assets is important once we focus on resilience rather than vulnerability. These other assets might provide alternative strategies for improving the system's resilience to the identified shocks and stresses.

The logic model in Chapter 3 provides a road map for the entire system, not just the physical network. In addition, the criticality of each of the assets needs to be identified, and the choice of metrics is important in order to be consistent with both a systems and a network perspective. From our AREA approach, reducing assets' criticality by reducing reliance on individual assets or the probability that an asset is taken offline would increase the resilience of the system. By having alternate routes or modes available or by expanding capacity, an individual asset would become less critical to the functioning of the system as a whole. This would increase the resilience of the system by avoiding cascading effects that could arise if a critical asset were taken offline. As AREA capacities increase, we are less likely to see disruptions in the system as a whole. At the same time, we will reduce the impact of disruptions and avoid cascading disruptions that could percolate through the transportation system. Additionally, by focusing on the entire asset base, alternative processes for increasing resilience might be realized.

Obtaining Hazard Data

As we discussed in Chapter 3, knowing which assets are exposed to what hazards is important to determine the shocks and stresses to which the system is building resilience. The VAF was developed for planning for climate change impacts. Therefore, the focus is on climate and weather-related events, including, for example, flood, drought, sea level rise, and extreme precipitation. Although climate and weather-related hazards are important, a wider array of hazards should be considered. In conversations with stakeholders, which we describe in Chapter 2 and Appendix A, transportation planners increasingly are concerned with potential cyberattacks on transportation assets and with exposure risks to other critical community assets, such as on energy production facilities, hospitals, and distribution centers. Therefore, distinguishing whether a given hazard is systemwide or would affect only a subset of the assets is important. Understanding the distribution of hazards across the system is important because there could be approaches to increasing resilience to multiple hazards with minimal additional investment that are not yet known. Knowing how hazards interact with the system also might reveal resilience investment strategies that are tied to reducing exposure rather than 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 and 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 are our focus because they are system-level approaches. The third approach is at the project level. In addition, more–data-intensive modeling approaches could be used but will depend on the capacity of the agency and available skill sets. Given our discussion in Chapter 4, 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 approaches that subject-matter experts could use to incorporate resilience from a systems-level perspective. Given the subjective nature of the stakeholder input process, many of the suggested improvements might go unnoticed.

Based on our discussion in Chapter 4, there is a suite of metrics that can be used to assess the resilience of the system that would incorporate both the criticality and exposure of the assets. The organization of the metrics in Chapter 4 allows for a direct translation of the AREA approach to appropriate metrics that could be considered in a resilience assessment. Developing these metrics at the system and asset levels will allow for greater resilience in both the assets and the system. Importantly, these two approaches can be combined as a check on the metrics. Not all aspects of the system can be quantified easily, and some might not fit into the suite of metrics that have been chosen. Therefore, incorporating institutional knowledge into the assessment can provide further context for assets or subsystems that lack resilience and alternative approaches to increase the resilience of the system.

The logic model and the AREA approach provide high-level system mapping and perspective on how the system would respond to the identified hazards. Because it might be difficult to assess how assets—and, therefore, the system—are affected by different hazards, it could be necessary to develop models that characterize how the chosen metrics respond to disruptions. It will be difficult to assess hazards without such models, especially when considering change in travel time or congestion, which are functions of the system capacities, demands, and potential disruptions. However, 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 approach, planners might see alternative solutions that could be considered in the next step. Understanding the transportation network as a whole—including noninfrastructure assets—and taking a systems approach will provide a rich set of data to inform stakeholders about the system. Importantly, knowing about the exposure and the consequences that arise because of the criticality of assets once they are disrupted is key to moving forward. It is not simply exposure or criticality that matter, but the combination of the two.

Identifying, Analyzing, and Prioritizing Options for Increasing Resilience

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

Once a suite of potential solutions has been identified, there are several techniques that can be used to evaluate and prioritize those solutions. For example, a multicriteria decision analysis can be used to highlight the trade-offs across different dimensions, such as environmental impacts, equity impacts, cost, feasibility, and changes in the metrics identified for measuring resilience. Knowing about the proposed solutions' (or projects') effects on the suite of metrics would allow each solution to be considered on a level playing field so that stakeholders would better understand the trade-offs involved in competing solutions. In addition, co-benefits could be identified that are outside the scope of the transportation system but might be of importance to the larger socioeconomic system or other systems in the system of systems.

In addition to multicriteria decision analysis, there is a suite of different economic analyses that can be used to evaluate solutions, including economic impact analysis, benefit-cost analysis, and life cycle cost analysis. There also have been efforts to apply the ideas of risk and resilience to hazards in an economic framework. For example, Bond et al., 2017, developed an approach for estimating a resilience dividend to compare different projects that might have similar targeted outcomes, where the *resilience dividend* is the aggregate difference between two projects, one of which takes a resilient approach and the other a traditional damage risk-reduction approach. Although the approach has not been applied to a transportation project specifically, it is general enough to allow for consideration of transportation projects. Each of these economic approaches has strengths and weaknesses and requires different technical skills and capacities that could be present in different organizations.

For example, if an asset is exposed to a hazard that makes it vulnerable to closure, there are several alternatives that should be considered rather than hardening the asset. The goal of the transportation network is to move people and goods where they need or want to go. By focusing only on absorptive capacity through hardening, such strategies as increasing adaptive capacity by adding alternate routes or alternative route capacity have not been considered. Additionally, prestationing of repair materials near the asset could provide additional restorative capacity. A combination of all of these increases in capacity could be more cost-effective and increase the resilience of the entire system. The focus should be on the resilience of the network rather than of an asset. 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 analysts. Therefore, the prioritization aspects should be considered in the next step. That is, the analysts should identify the key trade-offs across projects, while the decisionmakers should weigh those trade-offs in terms of the goals and priorities of the organization and the users it serves.

Incorporating Assessment Results into Decisionmaking

Incorporating resilience into decisionmaking is a cultural shift for most institutions in that 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 makes clear, the value of using resilience considerations is that the benefits of investments accrue during both normal and disrupted times (Bond et al., 2017). By taking a more holistic view of the transportation system and the variety of assets that are inputs to the system, decisionmakers must incorporate a wider set of considerations than risks and the impact of disruption into planning.

Resilience assessments should make information about alternative strategies accessible to decisionmakers. Providing the appropriate trade-offs to decisionmakers is important in order for them to understand how investments targeting the AREA concepts—not just damage risk reduction—can be incorporated into the suite of strategies available to increase the resilience of the system. The solutions identified by incorporating the AREA concepts, the system mapping identified in the logic model, and the dual concepts of criticality and exposure will allow for alternatives that should increase the functionality of the transportation system in both normal and disrupted operations. The value of incorporating resilience assessments into decisionmaking is that more–cost-effective approaches might be revealed by taking a more holistic approach to infrastructure. Thus, the focus should be on the outcomes, not the assets, in terms of the movement of people and goods to places where they are needed or wanted.

Although it might seem daunting to incorporate resilience into the entire assessment and planning process, the existing VAF can 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 incorporate resilience into the planning process.

6. Conclusion

Building resilience into the transportation system requires a change in perspective from protecting every asset to a systems-level view. It is not simply the direct transportation infrastructure that is important in building resilience; it is also the human and collaborative relationships. By mapping the system through the logic model discussed in Chapter 3, we provide a means to characterize the entire system, as well as the goals and outcomes the system is built to achieve. The AREA approach provides a means to develop the suite of strategies that is available to a planning organization working to build more resilience into its 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 system is the ideal, we can only improve the resilience of the system: There will always be exposures for which we cannot plan, either because they are outside the planning scope or at a scale outside the bounds considered. Most importantly, our goal in incorporating resilience is to build a system that functions better in normal and disrupted times.

Different planning organizations will have different goals. There is no one-size-fits-all approach to resilience. 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 give transportation planners the ability to relay the trade-offs for decisionmakers. Knowing how different projects target similar goals, how they achieve those goals, and at what cost will improve decisionmaking by expanding the suite of available strategies in order to achieve similar outcomes. How the system is modified is less important than how the system responds under different shocks and stresses. Having more information about alternatives to achieving similar ends can only improve the planning process.

Importantly, existing frameworks and assessment tools need only minor modifications to incorporate the concept of resilience more fully. It is more about the framing of the problem and the perspective planners take than the process of decisionmaking.

Appendix A. Stakeholder Interviews

The RAND team interviewed several transportation experts in order to understand the breadth of challenges and risks in transportation infrastructure planning and investment as well as the benefits to the transportation system and other systems that result from these plans and investments. The goal of these discussions was to better understand how stakeholders use information about 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 might influence their planning and investment decisions. The information gathered from these interviews was critical to ensuring that the outputs of this work are both valuable to stakeholders and feasible in terms of implementation. In this Appendix, we describe how we selected our stakeholder sample and the types of stakeholders interviewed. We then summarize the information derived from these discussions, which we used to inform the analytic framework presented in the body of this report.

Stakeholder Sample and Methods

For a system-of-systems approach to understanding transportation resilience, the RAND team selected stakeholders who would represent various types of transportation organizations in the United States. Transportation organizations face some similar and some different challenges but are connected in terms of effort, desired outcomes, or interjurisdictional areas or the transportation infrastructure itself. Stakeholders were from 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 variety of stakeholders allowed the RAND team to capture an understanding of all levels of transportation planning.

Sampling Methodology

Participant Recruitment and Selection

RAND researchers used convenience and snowball sampling to identify and recruit participants for interviews. These participants were found through (1) strategic online searches, (2) recommendations from the TRB advisory panel, and (3) recommendations by the RAND team of contacts who are subject-matter experts and practitioners.

The online searches included reviews of several official federal, state, and metropolitan planning organization websites to identify relevant stakeholders, such as the staff of a given state's DOT whose transportation planning experience included a transportation resilience intent. The search also included those for whom resilience was not a stated focus but whose work was closely linked to the topic: for example, state DOT emergency relief program staff engaged in disaster response. For the MPOs that were considered, RAND researchers targeted directors, planners, or team members who run a transportation resilience project and those who work closely with community partners and other state-level agencies and local jurisdictions. Federal-level stakeholders also were recruited to provide insight into their work in transportation resilience, an understanding of relevant federal requirements, and the big-system thinking that influences state-level DOTs and MPOs. Invitations were emailed to participants; the recruitment email is included at the end of this Appendix.

Final Sample and Interview Timeline

We conducted nine interviews at eight organizations over three months. We acknowledge that this is a limited sample in the U.S. transportation network, but we sought out nine interviews to fit our timeline that represented coastal locations and those in the interior of the country; international, state, and county borders; rural and urban areas; and areas with local routes and major commerce corridors (highways), such as I-10, I-70, and I-80. Although we tried to draw as geographically representative a sample as possible, of the 13 organizations invited to participate, we received no response from two MPOs and one state DOT. One state DOT declined to participate. This resulted in a 62-percent response rate for organizations contacted. In Table A.1, we list the organizational levels and locations of participants:

Table A.1. Transportation Stakeholder Locations

Level	Location	Organizations Interviewed
Federal	Washington, D.C.	2
State	Colorado and Iowa	2
MPO	Florida, Louisiana, Tennessee, and Texas	4

Interview Protocol

The interview questions were based on a semistructured 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, the disruptions were specific to their area. The full interview protocol is included at the end of this Appendix. The discussion included questions that, at a base level, were intended to capture the connectivity between transportation planning organizations; connectivity with organizations in other sectors (health, education, etc.); the benefits, costs, and challenges of the system; and current implementation and plans for dealing with shocks to the system. All of this information was discussed to understand transportation system resilience considerations and what is needed in the future to ensure a more resilient transportation system. The discussion items were tied to the development of the conceptual framework in parallel with the review of literature on transportation resilience. We asked questions about the stakeholders' roles, who they interact with for transportation planning and investment, their priorities, the costs and challenges they consider, the benefits they consider, how they use information to inform long-term planning and investments in highway and transportation infrastructure, and their perspectives 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.

What Stakeholders Are Saying About Transportation Planning and Resilience

In this section, we summarize the information provided by stakeholders in order of the questions asked in the protocol. These questions covered such topics as who organizations work with in transportation planning and investment, main priorities, challenges to transportation planning, and 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 of a resilient transportation system; how they measure—or would measure—these benefits; and their perspectives on the main factors that contribute to transportation resilience. We acknowledge that the topics discussed might not be reflective of all entities in the transportation network. This information is linked to the conceptual framework we discuss in Chapter 3 of the main report.

Organizations Working in Transportation Planning and Investment

The network of organizations involved in transportation planning and investment is broad and diverse. This breadth and diversity is especially important to understanding the system-of-systems framing of the transportation system because transportation network needs and challenges are diverse. We provide examples to illustrate the breadth and scope of the transportation planning network. However, we acknowledge that the depth and type of interaction among MPOs, state DOTs, and diverse organizations and sectors varies widely.

Representatives from the MPOs highlighted that day-to-day interactions with transportation-focused entities for planning purposes can include the county or counties in their jurisdictions, neighboring counties, member jurisdictions, and local and city governments. Also, some MPOs interact with other departments or offices in their host agencies, and some interact with the state for policy matters, preparation of their Transportation Improvement Program (TIP),[3] or financial planning. The following description from one MPO representative 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 might 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 interaction between state DOTs and MPOs, which can access databases that track the

[3] A TIP is a federal requirement for all MPOs, which must develop and maintain a multiyear plan for all transportation projects that receive federal funding (U.S. Department of Transportation, Federal Transit Administration, 2019).

current status of roads, their maintenance, and future construction. MPOs also might interact with multiple state DOTs 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 such issues as air quality and economic development, port authorities, and transit authorities (e.g., Memphis Area Transit Authority). Others mentioned advocacy organizations, such as AARP, and organizations focused on pedestrians, biking, and airports.

In addition to working with traditional transportation-related organizations or entities, MPOs also work with other sectors to achieve their goals. Examples from other sectors include local public works departments, school districts, and boards for planning efforts, such as safety in transportation or the proximity of a new school to transportation corridors. Other sectors that MPOs work with include local small businesses, other businesses, medical districts, hospitals, public health department 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 noted that

> 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.

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

> Its mission is to look at resiliency [across sectors]: housing, health care, transportation, water resources, health and environment, natural resources.

Other state-level stakeholders noted that they interact with FHWA and many other organizations, especially after a crisis, such as a disaster situation. This can include interaction with management at the U.S. Department of Homeland Security to connect local agencies with resources, the state 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 DOTs, including emergency specialists, planners, engineers, and policymakers to deal with resilience issues and 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 influencers in transportation planning and investment with whom they might interact only tangentially or not at all. This includes such organizations as local or grassroots advocacy groups; national institutes, such as the National Institute of Standards and Technology (NIST); other offices of state government, such as the office of tourism or development; divisions of public health and environment; those working in freight; and those working on and making decisions about land use. 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 and the entities they work with in transportation planning and investment. It became evident that, in some locations, resilience was a well-known concept and the conversation about resilience was ongoing. For example, according to two stakeholders,

> [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 multimodal 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 stakeholder noted that they were starting to inventory all of their resilience work and were reaching out to local planning departments, engineers, and flood plan managers to expand the conversation. A few others noted that small efforts were made to initiate this type of communication during meetings; such efforts might not yet be well coordinated; more effort is needed for better coordination; and some of these discussions depend on government acknowledgment and priorities at the state level, which raises the issue of funding. Some interviewees noted that the concept of resilience is not yet understood or agreed upon by different levels of government, and some perceived a lack of interest at the state DOT level. The importance of sharing information in a timely manner, such as after-action reports after major events, was mentioned. Stakeholders noted that it was important that this information be shared with MPOs in all locations affected 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 the transportation sector cannot affect private-sector building development codes or plans because developers are not engaged in the transportation conversations. This is a factor to consider in effective transportation resilience if, for example, 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 LRTPs. According to the U.S. Department of Transportation, LRTPs typically cover a 20-year time frame and describe the vision of the organization and ways to achieve it (see, for example, FHWA, Federal Transit Administration, and Volpe National Transportation Systems Center, undated). 23 C.F.R. § 135 directs states to consider certain issues as part of their statewide transportation planning processes. During interviews, some MPO stakeholders stated the following priorities:

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

MPO interviewees also stated their desire to ensure a safe system; enhance transportation options, including vehicles, bus services, greenways, and bike or pedestrian infrastructure; and ensure equity by providing more access to travelers in a given area. A review of MPOs' 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.[4]

State stakeholders emphasized priorities including safety; mobility with resilience incorporated; economic vitality; and resilience as the criterion for long-term investments, such as the national highway freight program. Following an event, priorities included safety, restoration of property, 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 proper courses of action to deal with flooding, which is resulting from increasing weather events and sea level rise. The options mentioned included rebuilding, rebuilding differently, or moving the infrastructure. In order to determine how to make the transportation system more resilient to such stresses and 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 funded by FHWA (U.S. Department of Transportation, FHWA, 2018c), none of the interviewees mentioned any universal funding streams for projects or system-level work related to achieving transportation resilience. One interviewee mentioned state-level interest in funds being compartmentalized for proactive investments. Interviewees from 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 requirements. However, representatives from MPOs also mentioned state funding for planning for disadvantaged communities, state bonds, fuel taxes, property taxes, and toll revenues. Other MPO interviewees said that they are starting to receive more local dollars from conservancies, individual donors, and developer impact fees. Some

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[4] This is a summary of information found on the websites of the following MPOs: Abilene, Texas; Adams County, Pennsylvania; Central Massachusetts; and Michiana Area Council of Governments, Indiana.

stated that achieving adequate levels of funding for transportation can be difficult, and one noted that 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. [The] legislature attempted to raise it last year and failed and we don't anticipate it being raised in [the] near future. It's gotten to the point where the state will no longer have enough funds to make a 20-percent match on major projects.

In emergencies, relief funds come from federal sources, such as FEMA or FHWA (U.S. Department of Transportation, FHWA, 2019), but interviewees noted that the processes for applying and receiving funds can be difficult. One stakeholder described a situation in which the thresholds and criteria to receive state-level emergency funding were understood, but the amount of emergency funding available was lower than needed. It also was noted that reimbursement for costs incurred in an emergency can be limited. Thus, while transportation organizations are obligated to maintain system safety after an emergency, the source for the necessary funds might be unclear.

Benefits Resulting from the Transportation System

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

Transportation provides a system for people to move around different regions. As one interviewee noted, the system also is

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

Transportation planning and infrastructure influence 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 and 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 divided roughly into three categories: (1) disruptions and risks, (2) challenges associated with planning and implementation, and (3) future challenges that will have to be accounted for in transportation resilience planning.

Disruptions and Risks

Disruptions and risks include

- extreme weather events, such as extreme heat, hurricanes, or winter storms that result in downed buildings, flooding, and storm surge. Flooding was the most-frequently mentioned of any source of disruption or risk from weather events.

- other physical threats, such as rockfall, wildfire, land loss and erosion, sea level rise, or destruction of industry infrastructure (e.g., 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

Challenges associated with planning and implementation include

- a lack of all-hazards planning and back-up plans (e.g., a freeze in an area that does not usually experience such events and lacks the resources—such as salt trucks—to deal with it) or, in the case of a shock or stress because of an emergency, a failure to formulate plans to evacuate people who lack access to a personal mode of transportation and no back-up plan if those systems also have 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, 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 among state, county, and city government priorities that have local impacts
- change in transportation planning management and slow adoption of new practices
- increased costs for labor and scarce resource materials, sometimes because of changing U.S. tariffs
- jurisdictional overlap, lack of clarity about who owns certain road infrastructure and who can—or who understands the need to—act to address issues that affect multiple jurisdictions
- unclear roles and responsibilities and workforce shortages.

Future Challenges

Stakeholders suggested that, in addition to current challenges that might be exacerbated over time, they will face various new challenges in transportation infrastructure planning and investment in the next five to ten years. The following list includes challenges currently faced by interviewees and future challenges:

- population growth, increased "mega-regions," and resulting increased congestion
- increased costs, for which funds might not be available
- policymaker support
- coordination of immediate and long-term planning with a shift in mindset to understand how a 20-year plan can be more useful than a short-term plan in an emergency and clarification of what constitutes an urgent issue (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 and increased amounts of impermeable surfaces
- increased freight traffic, resulting in increased wear and tear on such infrastructure as roads and bridges
- an increased need for maintenance and preservation.

Transportation Resilience

Definitions of Transportation Resilience

Although most MPO representatives 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 includes the FAST Act and FHWA Order 5520, which focuses specifically on transportation resilience related to climate change and extreme weather events (U.S. Department of Transportation, FHWA, 2015; U.S. Department of Transportation, FHWA, 2014). One federal stakeholder noted that DOTs are trying to develop guidance on integrating 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 should be tailored, narrow, tangible, and possibly expanded for the future.

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

Several stakeholders mentioned the importance of considering other sectors in their work in order to understand how transportation can affect the resilience of bigger systems and entire regions. Finally, one stakeholder noted that transportation resilience is the ability to learn from experience to better respond with the assets present in the system.

Resilient to What?

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

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

Some stakeholders mentioned concerns regarding maintenance of physical security. Specific issues raised included vehicle ramming attacks and threats to cybersecurity. One stakeholder summarized this concern:

> 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 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 with the public and improved warning systems would 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 the system level. However, this lack of data collection does not mean that 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 stakeholders mentioned using included crash data from DOTs; information on community participation in transportation; inventories of assets; information on costs and types of damage; road closure times; hours of delay; the use of cost-benefit ratios; the extended life of certain infrastructure, such as 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 mentioned other items that they are considering measuring to assess resilience. These items include the benefits of emergency relief, avoided disruptions, lives saved, environmental costs incorporated into economic analysis, the 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 include the time it takes for emergency services, such as shelters, to be set up; system vulnerability; portions of roads flooded on an annual basis; the frequency and costs of maintenance required for certain sections of infrastructure; the economic value of goods or freight in order to understand economic impacts during disruption; and an aggregate review 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 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 that could contribute to resilience in transportation infrastructure and the transportation system, including

- the need to create a source of funding specific to the goal and inform practitioners and planners about such funding
- the need to develop and implement resilience strategies for the short, medium, and long term
- the need to understand 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 sharing about floods to use in local mitigation planning and to predict challenges
- the need to consider both big, long-term risks and small day-to-day risks and be able to communicate them to decisionmakers
- the need to create better public address systems to communicate such information 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, p. 284)
- efficiency and designs that allow for less deterioration over time or for ease of repair and maintenance
- an understanding of critical assets and the costs when they are down because of an event, including secondary impacts of the disruption of those assets, such as the impact on the economy of disrupted access to jobs
- planning that incorporates infrastructure alternatives, such as roadway elevation; uses newer, more-permeable road materials; employs drainage or retention services; and is informed by hydraulics assessments 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.

Another noted that

> 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 [the] decisionmaking 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 the following suggestions:

- Stakeholders expressed a strong desire for more work in transportation resilience and suggested creating a culture shift that would make resilience efforts a national initiative with consideration of current investments and future risks.
- Interviewees clearly expressed the need to inform stakeholders in transportation and other sectors about what transportation resilience is, why it is important for planning, and the potential impacts on systems.
- Stakeholders' recommendations 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 that the standards should extend beyond transportation agencies in their applicability and should target each of the relevant audiences. They emphasized the importance of communicating 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 benefits of federal and state requirements related to transportation resilience and planning, many stakeholders cited the FAST Act, MAP-21, 23 C.F.R. § 667, FHWA Order 5520, and the National Environmental Policy Act (Pub. L. 114-94, 2015; Pub. L. 112-141, 2012; U.S. Department of Transportation, FHWA, 2014; 42 U.S.C. § 4321). In general, stakeholders welcomed these policies, and some expressed the belief that the policies stimulate motivation and interest in the resiliency space for those states not already working in it. However, some stakeholders found inconsistencies with how regulatory requirements for addressing resilience were understood and handled at the state and MPO levels and noted that only a handful of states have specific requirements.

Stakeholders made several suggestions, both broad and detailed, for practitioners, including

- a decision tool and criteria to incorporate resilience into transportation
- a 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
- a need for individuals, regions, and governments to recognize issues associated with climate change and take action.

Finally, stakeholders made several suggestions related to implementation, including

- a need for better design processes; for example, the need to better design work zones for major construction to ensure that drivers can traverse these sites safely and smoothly
- a need for better provision of information on construction plans and timing to drivers and passengers of public transportation

- application of the "build better" concept, for example, in systemwide drainage improvements and raised roads
- a need to review the congestion management process and shift the way people travel, including reviewing the quality of signs, paint markings, and other tools for driver communication.

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

Interview Recruitment and Protocol

Recruitment Email

Dear [participant name],

Hello, my name is [name] and I am a/an [title] 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 a 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, 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 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 at [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 your consideration and we hope to hear from you!

Sincerely,

[Signature Block]

Interview Protocol

Informed Consent

The RAND Corporation is working with the Transportation Research Board to develop an analytic framework for incorporating resilience into the Federal Highway Administration's Vulnerability

Assessment Framework. 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 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 specific individuals by name or affiliation without his or her permission.

Although documents related to this project could reveal the types of organizations that 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 [respondent organization] 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? [Choose from the following based on Q1 answer: city, district, county transportation officials from state department of transportation, metropolitan planning organizations, public transportation organizations of FHWA or Federal Transit Administration]

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 include neighboring governments and jurisdictions, hospital systems, educational systems, private-sector companies, police departments.]

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 in 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, and Challenges

6. What are the major disruptions to the transportation system and infrastructure in your area? By *disruptions*, we refer to congestion, potholes, and problems with physical aspects of the system.

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

8. What are the major challenges your organization faces in terms of highway and transportation planning? This includes funding, jurisdictional overlap, and trade-offs in terms of location.

9. What are the major issues that arise during planned implementation efforts or projects (e.g., unreliable contractors, supply of material inputs, available labor)?

10. Do you anticipate any new challenges for planning and infrastructure in the next five to ten years?

Transportation Resilience

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

Based on that [if not already answered],

12. What do you want to be resilient to?

13. From your perspective, what is the benefit of incorporating resilience into transportation planning? [Probe: Benefits to transportation 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 track these benefits or values with data? Do these data include certain performance measures? If so, what are they? Are any of these data available on your website (i.e., do you track the impact of transportation disruptions, safety, or operation and maintenance costs)?

16. Of the systems and sectors 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)?

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? Is there anything else we should consider when developing the analytic framework for transportation resilience and long-term planning?

20. Is there anyone else you recommend we talk with 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. Although the frameworks and analytic methods for traditional risk assessment are fairly mature, this is not necessarily the case for resiliency. There have been only a few systematic efforts to assess the most-effective strategies to build community resilience (National Research Council, 2012; Acosta, Chandra, and Madrigano, 2017). The main obstacles to identifying effective strategies are the lack of a widely accepted definition of resilience and a common framework for assessing and operationalizing it. In this Appendix, we describe major components of the concept of resilience and discuss past resilience definitions and frameworks that appear in the literature.[5]

Approach to the Literature Review

Our overall approach for the literature review was to develop a library of resources based on searches using widely available online databases and keywords relevant to each of the topic areas. We searched Google Scholar and Web of Science using the following keywords: "resilience," "resilience framework," "resilience conceptual," "resilience indicators," "resilience metrics," "resilience definitions," and combinations of these terms. We also used a database of literature developed at RAND on community response to climate change. These resources yielded a total of 1,318 articles. We reviewed the abstracts of these articles for the words "literature review" or "meta-analysis" to identify relevant literature for three topics: (1) the 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 in Norris et al., 2008. Our working definition is in line with that of the National Academy of Sciences, which appears in *Disaster Resilience: A National Imperative* (National Research Council, 2012). This is the definition currently adopted by the U.S. Department of Homeland Security. Our 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. We also considered more than 100 reports 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 context rather than an exhaustive list of frameworks. The

[5] The majority of the information in this Appendix has been presented by the authors in earlier publications but is included again because the information is fundamental to the framing of this work.

indicator systems are reviewed in Cutter, 2016, with a focus on systems that have been implemented. We include a larger discussion of indexes of interdependencies not present in the Cutter review that are directly related to the interdependencies that resilience is meant to capture. These indexes of interdependence link the frameworks considered and indicator systems that have been used by providing a metric for how interrelated the components of the system are.

Conceptual Foundations of Resilience

The concept of resilience has its foundations in materials science, mathematics, and physics, with a focus primarily on equilibrium analysis (Bodin and Wiman, 2004). Two main considerations in 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. 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 in the biological sciences, according to Holling, is that in biological systems, resilience and stability are clearly distinct. For example, while an ecological system might fluctuate and be unstable, it could be resilient to outside stressors. Holling's view suggests that the main concern of resilience is how large a stress the system can take while maintaining its integrity, as opposed to movement to a new equilibrium point.

Norris and colleagues, 2008, provides a broad overview of resilience definitions that have transitioned from the physical and biological sciences to the social sciences. We list these definitions in Table B.1. The main commonalities among all of the community-level definitions of resilience are threefold:

- *absorptive capacity:* How large a disaster or stress can a community absorb or resist and still function in the pre-event mindset? Some authors have 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 in the system that enable it 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? (It is understood that "normal" might look different after the event.)

The ideas underlying the study of resilience are linked (1) to other efforts that emphasize vulnerability and adaptive capacity and (2) 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 works 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 in the system (i.e., only the actors can perform actions that increase system resilience and reduce system vulnerability). Likewise, Cutter et al., 2008, p. 598, notes that the shift in focus from vulnerability to resilience among federal agencies might 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 on building underlying capacity to deal with future stressors, whereas mitigation efforts are limited to minimizing and repairing damage after the event (i.e., recovery).

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 aligned 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 complementary. Distinguishing between hazard mitigation and the recovery process, as many authors have done, could eliminate some potentially beneficial responses to risk. In particular, if the focus is solely on what happens after a disaster occurs, preemptive 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 might be ignored. A less vulnerable community is a more resilient community because it faces fewer disasters from which to recover.

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

Source	Level of Analysis	Paraphrased Definition
Gordon, 1978	Physical	The ability to store strain energy and deflect elastically under a load without breaking or being deformed
Bodin and Wiman, 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, Nicholls, and Thomalla, 2003	Ecological system	The ability of a system that has undergone stress to recover and return to its original state; more precisely (1) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction and (2) 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 retain essentially the same function, structure, and feedbacks—and therefore the same identity
Adger, 2000	Social	The ability of communities to withstand external shocks to their social infrastructure
Bruneau et al., 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 and Kulig, 1996	Community	The ability to recover from or adjust easily to misfortune or sustained life stress
Sonn and Fisher, 1998	Community	The process through which mediating structures (schools, peer groups, family) and activity settings moderate the impact of oppressive systems
Paton and Johnston, 2001	Community	The capability to bounce back and to use physical and economic resources effectively to aid recovery following exposure to hazards
Ganor and Ben-Lavy, 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 to cope effectively; the measure of adaptation and flexibility
Ahmed et al., 2004	Community	The development of material, physical, sociopolitical, sociocultural, and psychological resources that promote safety of residents and buffer adversity

Source	Level of Analysis	Paraphrased Definition
Kimhi and Shamai, 2004	Community	Individuals' sense of the ability of their own community to deal successfully with the ongoing political violence
Coles and Buckle, 2004	Community	A community's capacities, skills, and knowledge that allow it to participate fully in recovery from disasters
Pfefferbaum et al., 2006	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, Best, and Garmezy, 1990	Individual	The process of, capacity for, or outcome of successful adaptation despite challenging or threatening circumstances
Egeland, Carlson, and Sroufe, 1993	Individual	The capacity for successful adaptation, positive functioning, or competence . . . despite high-risk status, chronic stress, or following prolonged or severe trauma
Butler, Morland, and Leskin, 2007	Individual	Good adaptation under extenuating circumstances; a recovery trajectory that returns to baseline functioning following a challenge

SOURCE: Adapted from Norris et al., 2008, p. 129.

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. Because the transportation system is embedded in the larger socioeconomic system of systems and because of the networked 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 (Arup, 2014). As da Silva and Morera, 2014, p. 4, notes, "system-based approaches align more closely with the concept of resilience, and the long-standing notion of cities as 'systems of systems.'" However, da Silva and Morera reviews studies on subsystems rather than on the system as a whole, which leaves the interdependencies that arise across systems mostly unconsidered. In contrast, NIST, 2015, provides a broad overview of the components of community resilience from a system-of-systems approach and includes a chapter on these cross-system dependencies.

Da Silva and Morera, 2014, p. 7, notes the following about the City Resilience Framework:

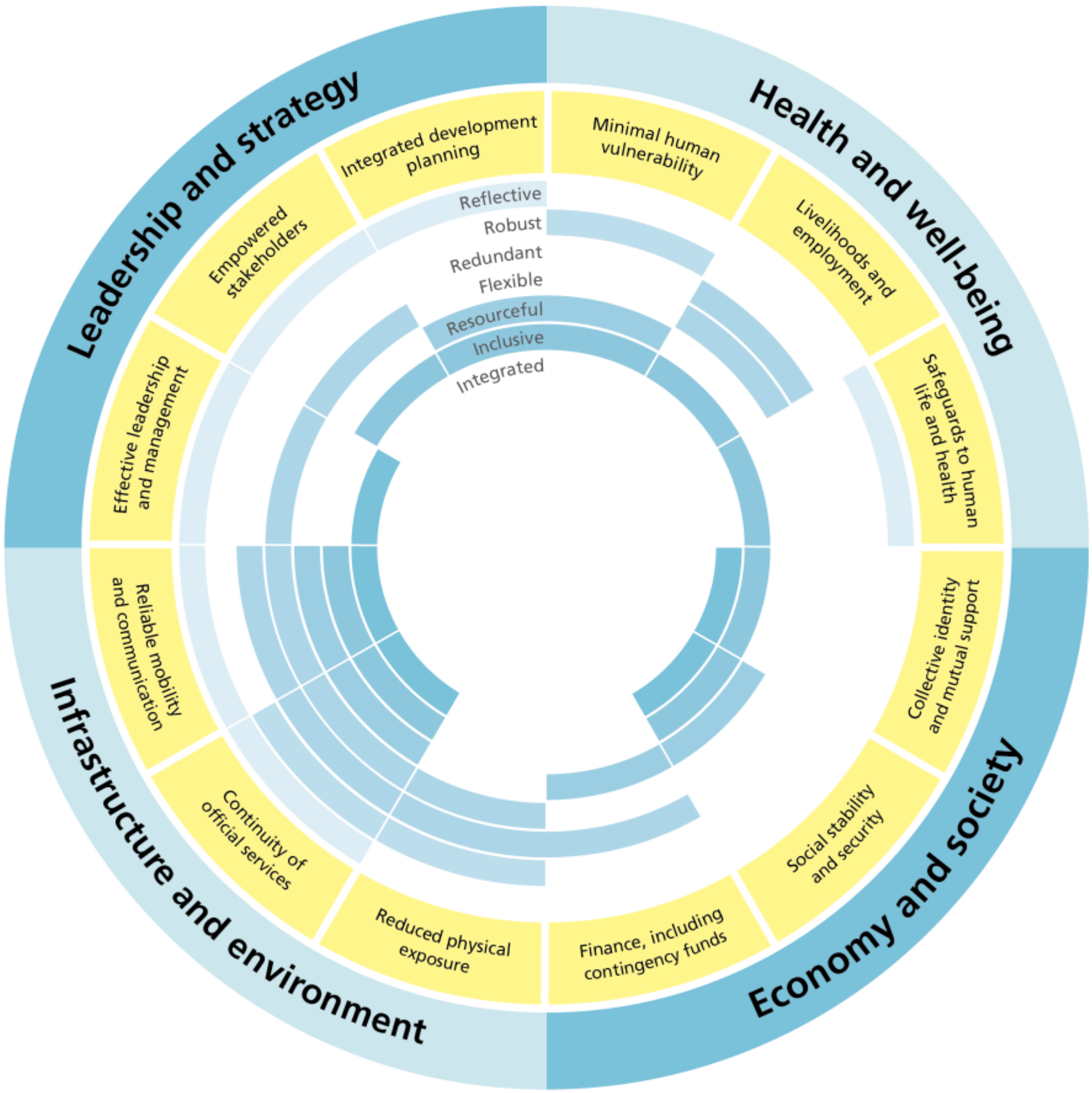
> Every city is unique. The way resilience manifests itself plays out differently in different places. The City Resilience Framework provides a lens through which the complexity of cities and the numerous factors that contribute to a city's resilience can be understood.

According to da Silva and Morera, resilient systems possess the following seven qualities. They must be

1. reflective: They should have mechanisms that continuously evolve.
2. robust: Systems should anticipate potential failures and make provisions to ensure that failure is not disproportionate to cause.
3. redundant: They should have spare capacity to accommodate disruption, pressure, and change.
4. flexible: Systems can change, evolve, and adapt.
5. resourceful: People and institutions should be able to find different ways to achieve their goals.
6. inclusive: The systems should promote community engagement.
7. integrated: Integration and alignment between systems should be pursued to promote consistency.

Da Silva and Morera's City Resilience Framework (Figure B.1) shows linkages across the various components of leadership and strategy, health and well-being, economy and society, and infrastructure and environment through the seven qualities of resilient cities described earlier. This framework integrates the individual systems through various channels.

Figure B.1. The City Resilience Framework



SOURCE: Adapted from da Silva and Morera, 2014, p. 9.

According to Rodin, 2013, resilient cities have the following 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. options 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.

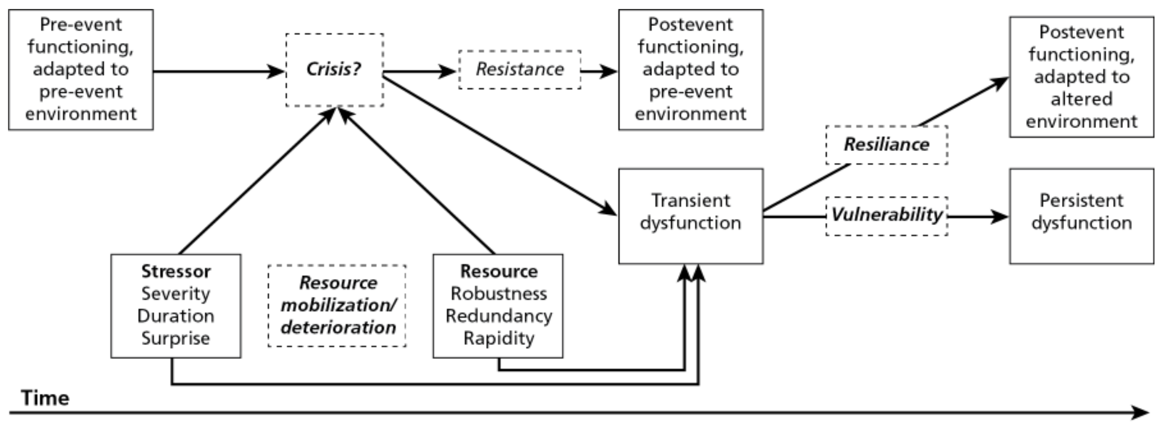
The characteristics of resilient cities according to Rodin aligns well with those of da Silva and Morera.

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, Teo, and Goonetilleke, 2013) distinguish among the ecological, economic, infrastructure, institutional, and social systems. Others (e.g., Bruneau et al., 2003) distinguish among the different infrastructure systems: hospital, electrical, water, local emergency management, and other systems. As discussed by Kahan, Allen, and George, 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, as discussed in Chapter 2 and Appendix A.

Norris and Colleagues' Resilience Framework

Norris and colleagues, 2008, provides a useful starting point from which to discuss alternative frameworks that inherently consider resilience (see Figure B.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 whether this stressor pushes the system to a crisis situation that is similar to shocks that the system can absorb or whether 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, adapting to a postevent 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. Although Norris et al.'s framework fails to account for feedback when a disruption has occurred, it does take into account the three major elements of resilience: adaptation, absorption, and recovery. Additionally, Norris et al.'s framework does not recognize that postevent 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 postevent funding opportunities that arise. As discussed in Godschalk, 2003, learning how to recover from events and preparing for future events takes places both in and across the communities.

Figure B.2. Framework of Resilience



SOURCE: Adapted from Norris et al., 2008, p. 130.

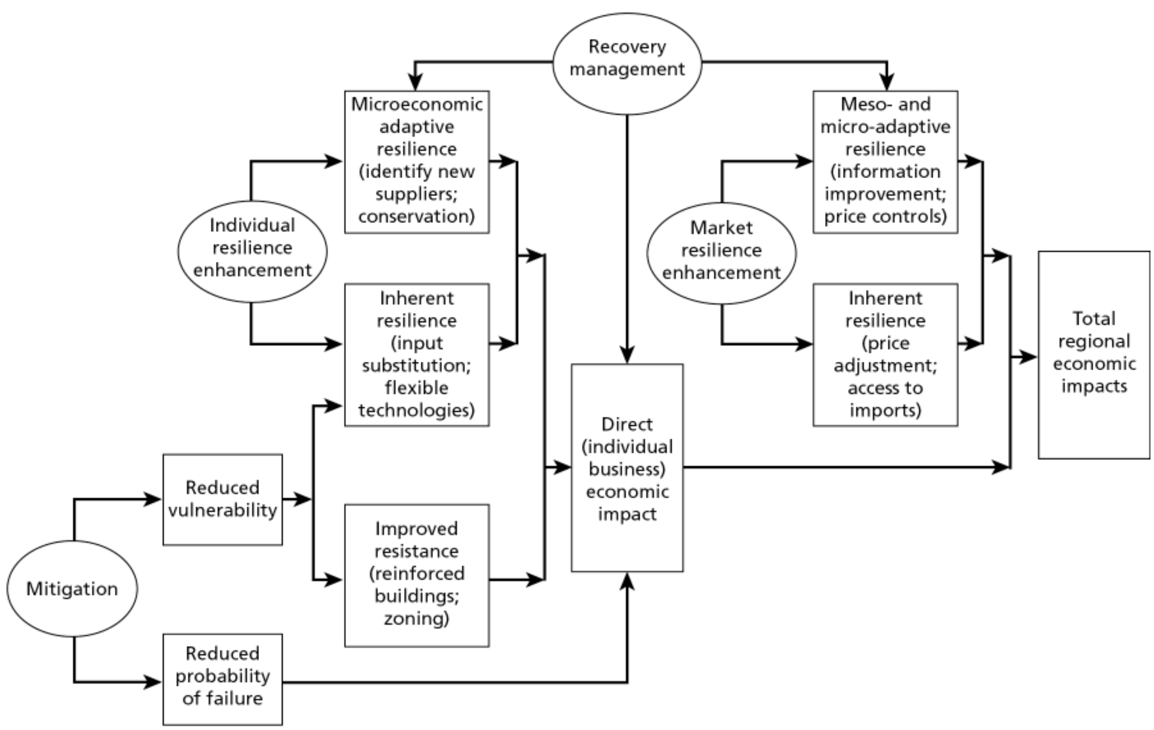
Rose's Framework and the Economic Impact of Mitigation

Rose, 2004, developed a framework (shown in Figure B.3) that is similar in structure to but more detailed than Norris et al.'s framework. The focus of Rose's framework is to understand the role of mitigation activities on total regional economic impact. Because of its focus on economic impact, this framework considers only the community's economic subsystem and not the broader social and natural environments, although the framework could 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 MOR. The framework's overarching goal is to minimize total regional economic disruptions, which are determined 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 an event might have. Thus, mitigation operates first to reduce the risk that a disruption will take place. Next, individuals and firms adapt to a changed environment by changing the inputs they use to produce goods and services and, ultimately, community well-being. How flexible the system is 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 (1) a reconstruction of capital that was lost to the disruption and (2) alternative production functions that might be more flexible and responsive to price signals the system sends to firms and households. In other words, how individuals and firms behave before, during, and after a shock (or in the presence of a stressor) are mitigating factors that influence the resilience of the system.

Although Rose, 2004, p. 308, uses a different definition of resilience—specifically, "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 the 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 it can be thought of in various spatial and organizational scales. Additionally, given the computable general equilibrium modeling that Rose uses, the linkages across sectors also are considered. If infrastructure is damaged, it affects a variety of sectors, and the impact cascades through the system because of the effects on both upstream and downstream supply chains. Additionally, Rose estimates the inherent resilience of a system because of the effects of mitigating activities and to improve understanding of how investments affect resilience.

Figure B.3. Economic Resilience Framework



SOURCE: Adapted from Rose, 2004, p. 311.

Francis and Bekera's Framework Focuses on Goals and Metrics

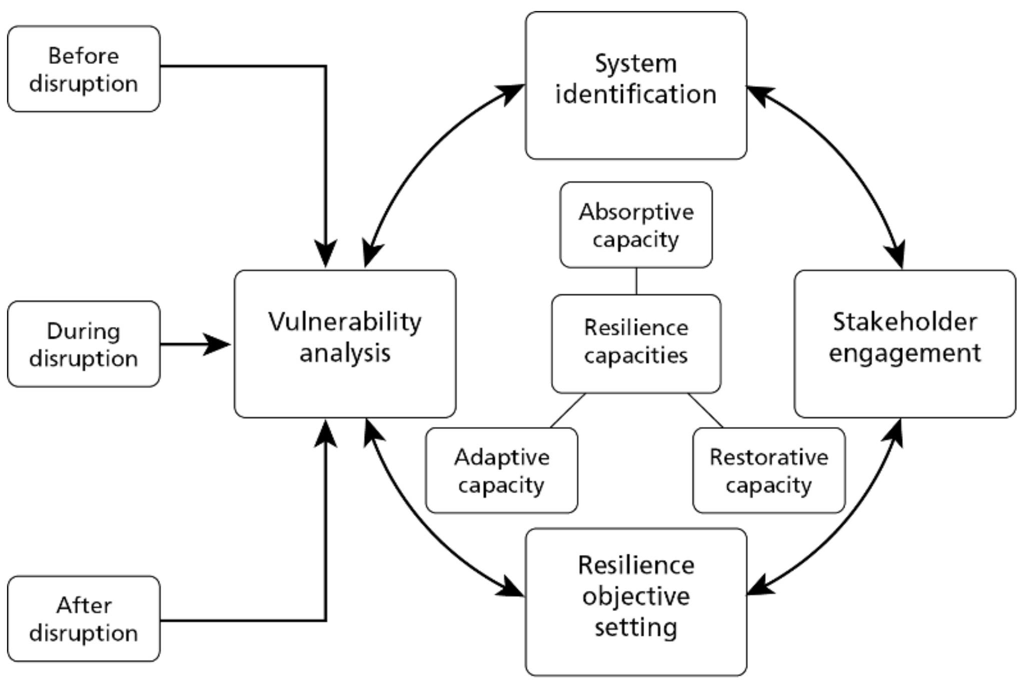
Combining the Rose and Norris approaches, Francis and Bekera, 2014, developed a framework that is more easily incorporated into a decisionmaking process (see Figure B.4). This framework has the following five components:

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 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 shows the three elements of resilience (adaptive, absorptive, and restorative capacity). These three elements also are present in the definition of resilience used to develop the framework. Furthermore, this framework incorporates risk governance through stakeholder engagement and objective setting as well as vulnerability analysis.

Figure B.4. Francis and Bekera, 2014, Resilience Framework



SOURCE: Adapted from Francis and Bekera, 2014.

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

Berke and Smith, 2009, pp. 15–16, provides the following ten principles of plan quality for hazard mitigation that could serve as a framework for resilience when moving from conceptual idea to practical implementation:

1. issue identification and vision

2. goals
3. fact base
4. policies
5. implementation
6. monitoring and evaluation
7. internal consistency
8. organization and presentation
9. interorganizational coordination
10. 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 focuses on consistency across the community as well as monitoring and evaluating progress toward the goals identified.

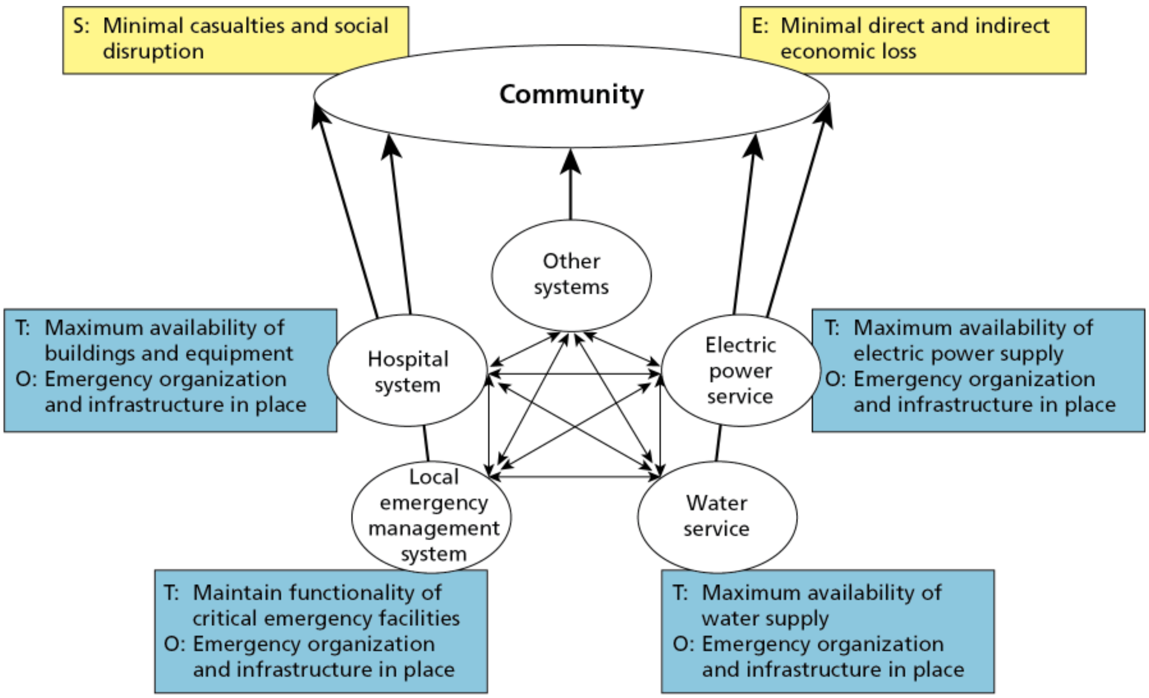
Cutter's Distinction Between Vulnerability and Resistance

Another perspective, that of Cutter, Boruff, and Shirley, 2003, and Cutter and colleagues, 2008, explicitly distinguishes between vulnerability and resilience. The major difference between the frameworks we have already discussed and the work of Cutter and colleagues is that vulnerability and resilience are distinct but interrelated concepts for Cutter et al. Cutter and colleagues' view is that resilience focuses on the adaptive nature of the system and not on the vulnerabilities embedded in it. Taking a broad view of resilience that encompasses the adaptive, absorptive, and restorative capacities of the system could reveal similarities among these definitions that can improve the well-being of a community. By making this distinction between vulnerability and resilience, these potential similarities might be lost. One key point these works recognize 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, which incorporates "with limited outside assistance" (Mileti, 1999). Resilience can be thought of as a more encompassing idea than sustainability but is linked in terms of postdisaster adaptation and recovery.

Bruneau and Colleagues' Focus on Critical Infrastructure

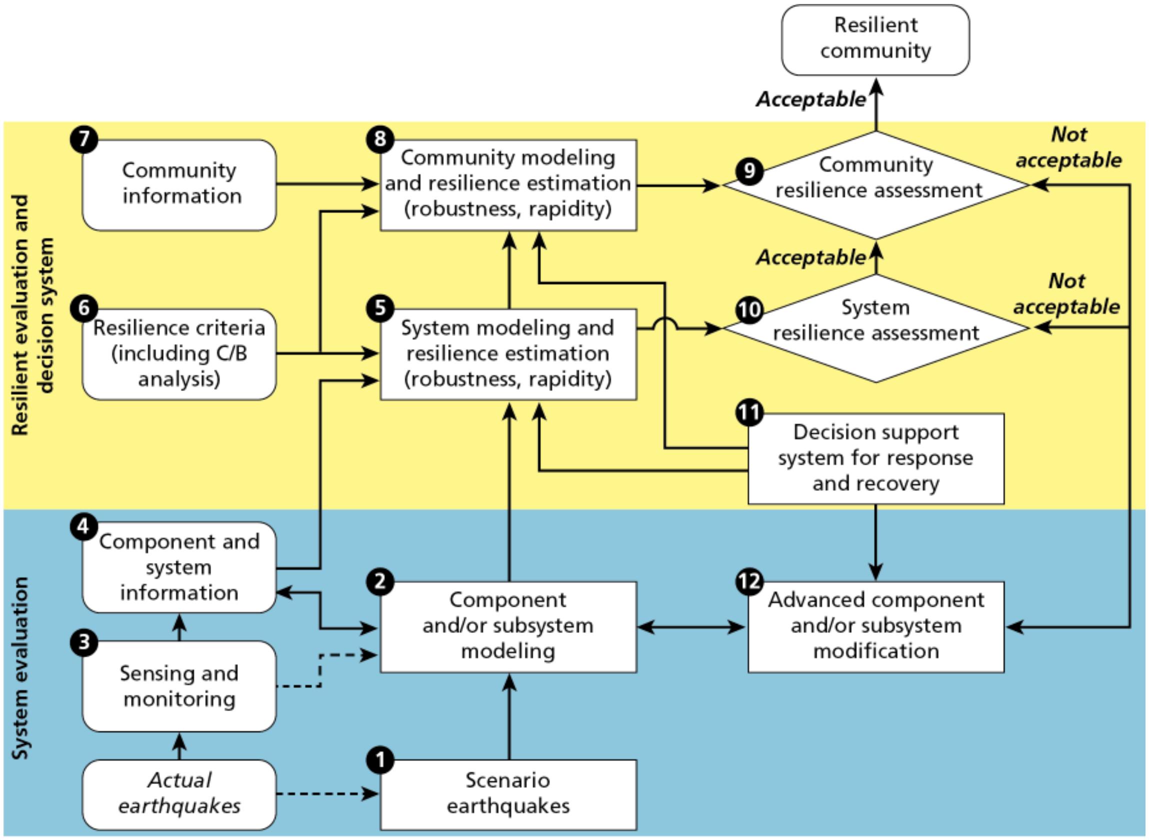
Unlike the previous frameworks, that of Bruneau and colleagues, 2003, focuses on critical infrastructure systems as opposed to social, economic, natural, and built systems (see Figure B.5). The starting point for this analysis is that resilience has four dimensions: technical (T), organizational (O), 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 in the critical infrastructure are key to understanding how events 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 (see 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 in the decision-support subsystem to continually modify the system until an acceptable level of resilience is achieved.

Figure B.5. Bruneau et al., 2003, Critical Infrastructure Resilience Framework



SOURCE: Adapted from Bruneau et al., 2003, p. 739.

Figure B.6. Interrelationships in the Bruneau et al., 2003, Framework



SOURCE: Adapted from Bruneau et al., 2003, p. 741.
NOTE: C/B = cost benefit.

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

Turner and colleagues, 2003, developed a framework that, although it focuses on vulnerability, is similar in spirit to that of Norris et al., 2008, but distinguishes between vulnerability and resilience, as in Cutter, Boruff, and Shirley, 2003, and Cutter and colleagues, 2008.

One of the main problems with the system-of-systems frameworks for analyzing resilience is that, as more systems are added, complexity increases, which complicates our understanding of the elements and relationships between them. Some frameworks quickly become muddled when trying to move from a conceptual framework to actual implementation because each 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 trade-offs 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 trade-offs. Given their finite budgets, communities need a decision-support tool for considering the trade-offs and complexities of investments in resilience. For a decision-support tool to be useful, the framework must incorporate the trade-offs the community is facing when building resilience. This decision-support tool should not make the decision for the community; rather, it should provide a level playing field for all participants in the decisionmaking process.

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

Mayunga, 2007, proposes an alternative view. Like the literature on economic sustainability, this view focuses 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 (see 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 rather than 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 capital stocks. Important substitution and complementary relationships among capital stocks affect the resilience that stems from the interdependencies.

Indicators and Metric Systems

Indicators and metric systems are bridges between the conceptual frameworks and the decision-support tools. In this section, we present an overview of the literature on resilience metrics, largely informed by the comprehensive review on the same subject in Cutter, 2016.

Many alternative indicator and metric systems have been used to measure the resilience of communities. There are four main reasons a community might want to develop or use a resilience indicator or metric system. First, such indicators could help characterize the system and bring awareness of shortcomings to the community (Prior and Hagmann, 2013). Second, they could provide a means to develop baselines and assess the progress of the community toward its goals. Third, these indicators might provide a broader view of the interdependencies of a system and how it reacts to various stresses (Linkov et al., 2014). Finally, metrics can be used in decision support and planning, but as Cutter, 2016, p. 743, 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.

It is difficult to develop a single system of metrics that can characterize resilience across different communities with vastly different exposures and risks. Additionally, most of the suites of indicators segment the systems rather than develop 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. Instead, they consider only indicators of subsystem resilience without the interconnections.

Cutter, 2016, provides the most comprehensive overview of the variety of indicator systems that have been used to date. She considers 27 different approaches that have moved from conceptual systems to implementation by at least one community. Cutter segments these 27 systems along several different dimensions. First, she segments them into three categories: indexes, scorecards, and tools. Indicators often are 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 versus bottom-up approaches. Top-down approaches allow for comparison across communities, whereas bottom-up approaches are tailored to the community where the assessment is taking place. One of the common characteristics of the systems identified by Cutter is that most develop indicators for the social, economic, institutional, infrastructure, and natural systems but lack links among these systems. The systems isolate the systems rather than consider the cascading effects and interdependencies inherent in resilience generally.

In addition to the 2016 review by Cutter, several other reviews, including Brooks, Aure, and Whiteside, 2014; Link et al., 2015; and Winderl, 2014, assess resilience metrics. Brooks, Aure, and Whiteside, 2014, notes that indicator systems are themselves conceptual frameworks. The focus of the Link et al., 2015, study is on developing a national-level resilience scorecard. It reviewed many of the same sets of systems as Cutter, 2016. The Winderl, 2014, study findings, which are similar to Cutter's, focus on measuring the resilience of subsystems rather than resilience at the community level. Unpublished research from the MITRE Corporation 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, 2016.

In addition to the systems discussed in the aforementioned reviews, there are various resilience indexes that have been considered. For example, Rose, 2007, considers the resilience of an economic system to shocks. Rather than focusing 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 in an economy can be captured in a relatively straightforward manner. Rose calculates the difference in 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 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 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 (2007) 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 the resilience of the system: the 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 allow for evaluation of the trade-offs 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 trade-offs that the system allows because of its interdependencies and networks.

Cutter, 2016, suggests, two main approaches that can be used to develop indicator systems: top-down or bottom-up. The distinguishing characteristic is whether the system is tailored to a particular community or is more general and applies to a variety of communities. Furthermore, the individual metrics for the subsystems overlap extensively, and the specific indicators used in the systems 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 analysis of resilience.

The overarching 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: There are cascading consequences across the system. This flaw also is found in the literature that measures the vulnerability of a system in the absence of considerations about exposure and hazards. A community might be vulnerable when measured using the SoVI (Cutter, Boruff, and Shirley, 2003), but if it does not face any hazards, is it really vulnerable? Similarly, one subsystem might not be very resilient, but if it is not an integral part of the community, it might not affect 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, we can understand the resilience of a community more thoroughly. The indicator systems and indexes need to better incorporate the frameworks 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. Furthermore, we were unable to identify articles that provided a validation of the indicator or metrics 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 whether communities that have higher levels of resilience based on any resilience metric recover more quickly or to a higher level of functioning.

Gao, Barzel, and Barabási, 2016, developed a method to collapse multidimensional complex networks into a single summary metric of resilience. In its metric, the network topology 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 (1) density of the connections in the system, (2) heterogeneity of those connections, and (3) 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. For example, if subsystem A affects subsystem B, then subsystem B affects subsystem A. Additionally, a 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 indexes tend to reduce the information available to decisionmakers rather than enhance understanding. Weighting is a function of the values of the individual setting the weights and thus should be part of the public discourse about trade-offs among multiple competing objectives.

Summary

All of the frameworks within the system-of-systems literature provide different approaches to tackling roughly the same problem: How should we conceptualize a large number of independent systems that interact with each other, either through functional or infrastructural segmentation? Each of these frameworks appeals to different types of analyses and different views about the world. The Rose framework (2007) provides a useful starting point, if focused only on the economic system, for considering the interactions that occur and how adaptation could be enhanced. Norris et al., 2008, provides 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. Also, 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 of the potential relationships that might take place in a community.

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