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Investing in Transportation Resilience

A Framework for Informed Choices

Committee on Transportation Resilience Metrics

A Consensus Study Report of
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Preface

H.R.1865—Further Consolidated Appropriations Act, 2020, calls on the "Secretary of Transportation to enter into an agreement with the National Academies of Sciences, Engineering, and Medicine to conduct a study through the Transportation Research Board on effective ways to measure the resilience of transportation systems and services to natural disasters, natural hazards, and other potential disruptions." To conduct the study, the National Academies appointed a committee of 12 experts in the fields of multimodal transportation infrastructure, transportation policy and decision making, resilience, economics, and risk analysis tools. This report represents the consensus efforts of these 12 individuals, who served uncompensated in the public interest. Their biographical information is provided in Appendix A.

ACKNOWLEDGMENTS

The committee met 14 times from May 2020 to April 2021 to gather information relevant to the study and to deliberate on the report contents, findings, and recommendations. Four of the meetings included briefings and discussions with experts from the transportation agencies and organizations on existing and planned uses of resilience decision-making frameworks, methodologies, metrics, and related data.

The committee wishes to thank the following individuals for participating in these briefings and making other contributions to the committee's work:

Matthew Arms, Port of Long Beach; David Ferryman, EVRAZ North America (formerly with CN); Robert Germann, U.S. Army Corps of Engineers; Angela Gladwell, Federal Emergency Management Agency; Robert Kafalenos, Federal Highway Administration; Elizabeth Kemp, Colorado Department of Transportation; Jeffrey Meek, Minnesota Department of Transportation; Brendan Reed, San Diego County Regional Airport Authority; Porie Saikia-Eapen and Andrew McMahan, New York Metropolitan Transportation Authority; and Dale Stith, Hampton Roads Transportation Planning Organization.

The committee also wishes to thank Alasdair Cain, U.S. Department of Transportation, and Josephine Eckert, U.S. House of Representatives, for participating in the first committee meeting and sharing their insight on the study.

Monica A. Starnes directed the study and assisted the study committee in the preparation of this report under the guidance of Thomas R. Menzies, Jr. Sarah Jo Peterson supported the writing of the report.

The report has been independently reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures specified by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will help ensure that the report is balanced and evidence-based and satisfies institutional standards for objectivity and responsiveness to the study's charge. The reviewers' comments and the draft manuscript with which they were provided remain confidential to protect the integrity of the deliberative process.

The committee thanks the following individuals for their review of this report: Peter Cafiero, Washington Metropolitan Area Transit Authority; Katherine Chambers, U.S. Army Corps of Engineers; Ginger Evans, CAG Holdings LLC; Geoffrey Heal (National Academy of Sciences), Columbia University; Jennifer Jacobs, University of New Hampshire; Brendan Reed, San Diego County Regional Airport Authority; Carol Lee Roalkvam, Washington State Department of Transportation; Eugene Seroka, Port of Los Angeles; Kumares Sinha (National Academy of Engineering), Purdue University; and Sharon Wood (National Academy of Engineering), The University of Texas at Austin.

Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the committee's conclusions and recommendations, nor did they see the final version of the report before its release.

The review of this report was overseen by Chris T. Hendrickson (National Academy of Engineering), Carnegie Mellon University (emeritus), and Ross B. Corotis (National Academy of Engineering), University of Colorado Boulder. Appointed by the National Academies, they were responsible for making certain that an independent review of the report was conducted in accordance with institutional procedures and that all review comments were carefully considered by the committee. Responsibility for the final content of the report rests solely with the authoring committee and the institution. Karen Febey, senior report review officer, Transportation Research Board, managed the report review process.

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APPENDIXES

Acronyms and Abbreviations

AI	artificial intelligence
BCA	benefit-cost analysis
CMIP	Climate Model Intercomparison Project
DOT	Department of Transportation
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
HRTPO	Hampton Roads Transportation Planning Organization
IN-CORE	Interdependent Networked Community Resilience Modeling Environment
LACMTA	Los Angeles County Metropolitan Transportation Authority
NFIP	National Flood Insurance Program
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration

OST	Office of the Secretary of Transportation
PRAISys	Probabilistic Resilience Assessment of Interdependent Systems
RAMCAP	Risk Analysis and Management for Critical Asset Protection
RDRM	Resilience and Disaster Recovery Metamodel
SoVI®	Social Vulnerability Index
SPUR	San Francisco Planning and Urban Research Association
STIP	Statewide Transportation Improvement Program
TAZ	Traffic Analysis Zone
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation
USGS	U.S. Geological Survey
VAST	Vulnerability Assessment Scoring Tool
WMATA	Washington Metropolitan Area Transit Authority

Executive Summary

Storms, floods, droughts, and other natural hazards are combining with sea level rise, new temperature and precipitation norms, and other effects from climate change to increase the vulnerability of the nation's transportation systems. The United States experienced a record-breaking 22 billion-dollar natural disasters in 2020. To varying extents, all damaged or disrupted the operations of transportation infrastructure vital for emergency services, evacuations, and the movement of supplies. Costly infrastructure repairs strained state and local budgets, and the disruptions to transportation networks and services adversely affected local and regional economies and the safety and well-being of people in affected communities.

Long-lived—with design lives of more than 50 years—and ubiquitous, transportation systems have always been exposed to a wide range of natural hazards and their inevitable extremes. However, climate change is compounding the intensity and expanding the scale of natural hazards. It is increasing the likelihood of cascading events, where multiple hazards interact, and it is creating new stressors on transportation assets constructed for different temperature and precipitation norms. Meanwhile, the smooth and safe functioning of transportation infrastructure is being stressed from everyday use. Across the country, many major transportation assets have outlasted their planned service lives by decades yet continue to be essential for accommodating traffic flows at levels unimagined in their original planning and design. Under these circumstances, ensuring that transportation systems are resilient—that is, able to withstand and recover rapidly from adverse conditions and events—has become vitally important but increasingly challenging.

This report reviews current practices by transportation agencies for evaluating resilience and conducting investment analysis for the purpose of restoring and adding resilience. These practices require methods for measuring the resilience of the existing transportation system and for evaluating and prioritizing options to improve resilience by strengthening, adding redundancy to, and relocating vulnerable assets. The review reveals that significant progress has been made over the past decade in integrating resilience criteria into transportation decision making, including the development, piloting, and use of innovative tools for resilience measurement, evaluation, and investment prioritization. However, the review also finds much inconsistency in how resilience is measured and assessed, even when it is a prominent factor in the transportation investment planning and decision-making process.

In addition to reviewing practice, the report examines the research literature on resilience theory to understand concepts and methods that may be suitable for implementation by transportation agencies. The literature review reveals a wide and rich variety of promising analytic methods, as well as ideas for their potential application. However, not surprisingly, the complexity of planning, building, and operating transportation systems can complicate the transition of research into practice, necessitating continued investments in applied research and in the demonstration and piloting of research ideas and concepts in the field.

This report's review of both practice and research suggests that more can be done to make the calculus of resilience a more systematic and deliberate part of transportation asset management and investment decision making. The review suggests that resilience should be measured and assessed using a multi-step, multi-hazard analytic framework. The process of assessing the potential benefits of resilience investments includes detailed inventories of assets that exist and are planned; evaluations of the characteristics and likelihood of natural hazards occurring in the future; and predictions of the vulnerability of the inventoried assets to disruption, damage, and destruction from the hazards. These assessments should be accompanied by determinations of the criticality, or value, of each asset's functionality and estimations of the consequences of damages to the asset and its lost or degraded functionality. The avoidance of future losses in functionality, as incurred by infrastructure owners and users and the broader community, represents the societal benefits of effective resilience investments. The Federal Highway Administration (FHWA) has been particularly active in piloting frameworks for resilience analysis that follow this approach.

Investing in resilience requires spending funds in the present to gain some benefits that may or may not be realized in the immediate or mid-term future. The decision to make a resilience investment must consider its prospective benefits and likely costs, including financial outlays and other sacrifices, both accrued over the life cycle of the investment. Benefit-cost analysis (BCA) is the analytic tool often used to support such decision making. While translating benefits and costs into monetary values facilitates BCA, resilience investments can also be evaluated using quantitative, non-monetary measures and qualitative descriptions to account for the full set of possible outcomes, including equity and distributional consequences. Some analysts refer to BCA as social BCA because it considers "all of the benefits and costs to society as a whole, that is, the social costs and the social benefits."[1] A BCA that yields results showing positive net benefits represents the societal gain from a resilience investment that takes into account its life-cycle costs and benefits.

To carry out resilience benefit assessments, transportation agencies need high-quality data and analytic tools, and in particular

- Information on the characteristics of natural hazards and their likelihood in the location of existing and planned assets;
- Science-based and updated projections about future impacts of climate change on natural hazards and on temperature and precipitation norms in these locations;
- Strong asset management programs that include evaluations of asset vulnerabilities and estimation of functional values (i.e., criticality);
- Mode-specific data and modeling tools to estimate the direct and indirect consequences of asset damage and functional losses; and
- Data and modeling tools that can reveal the economic and social importance of the asset to users, directly affected communities, and the broader region. Where there are gaps in essential data and in the needed analytic tools, transportation agencies may need to tap expert judgment.

In addition to revealing the importance of transportation agencies having access to high-quality data and analytic tools for making sound investments in resilience, this report points to the importance of pilot activities for showing how resilience evaluations can be made a routine part of investment decision making and for demonstrating the application of these data and tools for this purpose. The report shows how well-structured pilot programs and demonstration projects have been playing an important role in furthering the state of practice and application of resilience analysis for transportation decision making. However, these programs remain limited in their scale and scope, and in the absence of better and more accessible data and analytic tools coupled with more piloting, transportation agencies

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[1] Boardman, A., D. Greenberg, A. Vining, and D. Weimer. 2006. *Cost-Benefit Analysis: Concepts and Practice*, 3rd edition. https://doi.org/10.1017/9781108235594.

are likely to continue to struggle with the translation of resilience from a concept to a decision criterion.

While this report could not identify a single metric, or even a small set of metrics, that can be readily developed and generally applied to ease this struggle, it does outline a systematic framework for making resilience a key part of the investment calculus. Analyses that use appropriate metrics within a strong decision support framework can help make the case for investments in resilience. A decision-making framework alone, however, will not suffice because transportation agencies will lack the requisite data and analytic tools for its implementation or the demonstrations of its use. To motivate and facilitate the framework's use, more direction, prompting, and guidance are needed. The recommendations that follow are offered for these purposes. They are targeted to Congress and the U.S. Department of Transportation, but their aim is to strengthen the resilience practices and capabilities of thousands of state, regional, and local transportation agencies.

RECOMMENDATION 1:

To ensure the routine and deliberate consideration of resilience to support the selection of major transportation investments, **Congress should consider a requirement for which all projects that involve long-lived assets and that are candidates for federal funding undergo well-defined resilience assessments that account for changing risks of natural hazards and environmental conditions stemming from climate change. These assessments could be integrated into environmental impact assessments or other project evaluation efforts, such as during benefit-cost analysis. The level of analytical effort expected in these resilience assessments should be reasonably related to the cost of the project being considered.**

Each project's selection should include the results of analyses in which resilience benefits are calculated through a multi-step analytic framework that includes assessments of all plausible natural hazards and their likelihood, including simultaneous and cascading hazards; the vulnerabilities of the asset to damage and disruption from the hazards; and the adverse consequences from the damage and disruption to functionality as they impact the owners and users of the assets and the broader community.

RECOMMENDATION 2:

The Office of the Secretary of Transportation should promote the use of benefit-cost analysis for project justifications that take into account the resilience benefits estimated using the multi-step analytic framework recommended above. The benefits from adding resilience, in the form of reduced

future losses, in relation to the life-cycle costs of doing so should be promoted as the basis for selecting investments in resilience.

Although the practice of BCA is often associated with an overemphasis on the benefits and costs that can be more confidently monetized, the nature of resilience impacts, coupled with the demands of practical decision making, call for analyses that are attentive to all important effects, whether represented in monetary, quantitative, or qualitative terms. The Office of the Secretary of Transportation should offer guidance on how important benefits and costs that cannot be reduced to monetary units can be appropriately incorporated in BCA.

RECOMMENDATION 3:

The Office of the Secretary of Transportation should provide guidance to the U.S. Department of Transportation modal administrations on the development of analytic methods and tools for estimating resilience benefits that are applicable to transportation agencies in their respective modes.

The guidance should build on lessons learned from initiatives by FHWA and other federal and state agencies to pilot analytic approaches like the multi-step framework recommended above for use in assessing resilience on major transportation projects receiving federal funds. The guidance should point to the kinds of data and analytic tools required to perform each step in the assessments, and it should explain how the results can be used in BCA for decision making that incorporates resilience.

RECOMMENDATION 4:

Congress should direct, and appropriately resource, the Office of the Secretary of Transportation to conduct a study to (1) define the types of data that transportation agencies need for resilience analysis in accordance with the framework recommended above; (2) identify potential sources of these requisite data; and (3) advise on possible means for making the data more suitable to this purpose, including filling key data gaps and ensuring timely data updates.

This study will require consultation with other federal agencies such as the Federal Emergency Management Agency, the National Oceanic and Atmospheric Administration, the U.S. Forest Service, and the U.S. Geological Survey, where much of the data needed for resilience analysis are maintained, on means for transportation agencies to acquire the information in the format and level of detail needed, for keeping it sufficiently up to date, and for obtaining additional information that is not currently gathered. The study should note where new statutory authorities and appropriations may be required to enable these purposes.

RECOMMENDATION 5:

The Office of the Secretary of Transportation should coordinate with the modal agencies on the design and conduct of structured pilots to assess and demonstrate the applicability of each agency's guidance and suggested tools for estimating resilience benefits according to the recommended multi-step analytic framework.

FHWA's series of pilot programs for highway resilience analysis should be used as a model for these structured mode-specific pilots, which have led to increased state and local transportation agency familiarity with resilience analysis and to continual improvements in FHWA's guidance on analytic methods and appropriate tools.

1

Introduction

The reinsurer Munich RE reported in January 2021 that in the preceding year, 6 of the world's 10 most costly natural disasters occurred in the United States.[1] The most destructive was Hurricane Laura (Category 4 with winds of 240 km/h), which landed near Lake Charles in western Louisiana during August 2020. Its heavy winds, rain, tornadoes, and storm surge caused extensive flooding in the Gulf Coast states, with economic losses exceeding $13 billion. According to the Louisiana Department of Transportation and Development, water damage from this storm eroded and undermined roadbeds; overtopped and damaged the mechanics of movable bridges, threatening marine travel; and spawned debris and high water that led to the closure of thousands of miles of highway, including the state's longest and most heavily traveled Interstate bridge.[2] Such large-scale natural disasters that wreak havoc on the condition and functioning of transportation systems and other infrastructure are on the rise. During the 1980s,

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[1] Munich RE. 2021. "Record Hurricane Season and Major Wildfires—The Natural Disaster Figures for 2020." https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/media-information/2021/2020-natural-disasters-balance.html.

[2] LADOTD (Louisiana Department of Transportation and Development). 2020. "DOTD Request for Quick Release of Emergency Relief Funds to Assist with Hurricane Laura Damage Approved." Press release, September 4. http://wwwapps.dotd.la.gov/administration/announcements/Announcement.aspx?key=24327; Austin, N. 2020. "Most of I-10 Reopens in Louisiana Post-Hurricane Laura." *FreightWaves*, August 28. https://www.freightwaves.com/news/breaking-news-most-of-i-10-reopens-in-louisiana-post-hurricane-laura.

billion-dollar natural disasters, when adjusted for inflation, averaged 2.9 per year, but in 2020 alone the United States experienced more than 20.[3]

Beyond these disastrous events, climate change is bringing about slow but persistent changes in sea level and temperature and precipitation extremes that are intensifying storm damage and accelerating infrastructure deterioration.[4]

The country's highways, ports, waterways, airports, railways, and public transit systems are vital to the economy and everyday lives of Americans. In the periods immediately before, during, and after natural disasters they are essential for evacuations, rescue, and access to critical supplies and services. Keeping their key components open and functioning as lifelines during the onset and in the midst of a natural disaster can be an imperative for emergency response, while rapid and safe restoration afterward can be foundational to communities and commerce in recovering and regaining a semblance of normalcy. The term for this capability to resist and rebound is "resilience," and because transportation systems have critical local, regional, and national functions, the development and maintenance of this capability is a vital interest of governments across all jurisdictional levels and of the private sector.

Because the responsibility of transportation agencies and industries is to invest to assure needed functionality, knowing how well that functionality will be preserved, replaced, and restored under conditions of stress from natural hazards and climate change is an inherent part of the investment calculus. Determining and measuring the resilience benefits conferred by investment choices, however, can be challenging because transportation assets are exposed to many kinds of natural hazards and hazard extremes over their long life spans, and they are part of larger systems that function on different spatial scales. What may seem to be a localized investment in a transportation asset could have broader implications on the functioning of the transportation system over a larger geographic region, including the system's ability to compensate for other parts of the system that may become compromised by premature degradation or a disruptive event. A full and explicit accounting of resilience benefits would affect the decision calculus of many transportation investments.

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[3] The National Oceanic and Atmospheric Administration's (NOAA's) calculations of billion-dollar events are adjusted for inflation. See NOAA NCEI (National Centers for Environmental Information). 2021. "U.S. Billion-Dollar Weather and Climate Disasters." https://doi.org/10.25921/stkw-7w73.

[4] Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, eds. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.

Although most of the country's public-sector transportation infrastructure is owned and operated by state and local governments, the federal government has much at stake in ensuring that sufficient, effective, and timely investments are made to deliver a resilient national transportation system. The preservation and rapid restoration of the many important local and regional functions of transportation systems is in the public interest generally, and it is in the national interest to avoid disruptions that cascade across broader transportation and logistics networks, threatening economically and socially critical supply chains. Accordingly, when transportation assets are damaged and do not operate efficiently, and system functionality is lost or seriously degraded in disasters, the federal government will often step in to provide emergency relief and recovery funding assistance.

In recent years, the federal government has increasingly stressed the importance of enhancing the resilience of transportation systems when reauthorizing and amending both its regular federal aid programs and its post-disaster emergency relief programs. For example, the 2015 Fixing America's Surface Transportation Act requires that statewide and metropolitan long-range highway and transit improvement plans consider projects and strategies to improve the resilience and reliability of the transportation system.[5] For its Port Infrastructure Development grants, the Maritime Administration encourages applicants to take into account climate change in project planning efforts and to include project components dedicated to mitigating or reducing impacts of climate change.[6] In responding to the aftermath of Hurricane Sandy in 2012, Congress authorized the Federal Transit Administration to set aside funding for communities impacted by the storm to compete for grants to cover public transit projects intended to reduce current and future vulnerabilities to disasters.[7] The federal interest in building resilience into public infrastructure is also exemplified by the new Federal Emergency Management Agency (FEMA) Hazard Mitigation Assistance Grants program, which will award funds competitively for projects intended to increase a community's resilience before a disaster affects an area.[8]

As resilience has become a more explicit and prominent goal for the allocation of transportation funding assistance, there is a growing interest

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[5] FAST Act, H.R.22, 114th Cong. (2015–2016). https://www.congress.gov/bill/114th-congress/house-bill/22/text.

[6] U.S. DOT (U.S. Department of Transportation), Maritime Administration. 2021. "Frequently Asked Questions—Port Infrastructure Development Grants." https://www.maritime.dot.gov/PIDP%20Grants/FAQs.

[7] FTA (Federal Transit Administration). 2013. "Notice of Funding Availability for Resilience Projects in Response to Hurricane Sandy." https://www.transit.dot.gov/regulations-guidance/notices/2013-30867.

[8] FEMA (Federal Emergency Mangement Agency). 2021. "Hazard Mitigation Assistance Grants." https://www.fema.gov/grants/mitigation.

in clear and reliable metrics that convey the degree of resilience already in the transportation system and that would be added by well-planned and targeted public investments in infrastructure and recovery capacity. Many considerations go into the prioritization of transportation investments, some of which are more quantifiable (such as traffic impacts) than others (such as quality of life impacts). In an environment where the risks and natural disasters are growing and their costs are escalating, the measurement of resilience is becoming even more important for making transportation investment choices that are sound and do not leave the strengthening of this capability to chance. It is presumably that interest in making investment choices that are well informed by resilience considerations that led to the request for this study on metrics, the details of which are discussed next.

STUDY CHARGE

On December 20, 2019, the Further Consolidated Appropriations Act, 2020, Division H—Transportation, Housing and Urban Development, and Related Agencies Appropriations Act directed the U.S. Department of Transportation (U.S. DOT) to enter into an agreement with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to conduct a study through the Transportation Research Board on effective ways to measure the resilience of transportation systems and services to natural disasters, natural hazards, and other potential disruptions.[9]

In commissioning the study in response to this legislative request, the U.S. DOT's Office of the Assistant Secretary for Research and Technology and the National Academies negotiated the following more detailed Statement of Task:

> The committee will identify and examine metrics that can be used to assess the resilience of existing infrastructure and inform the planning of investments in infrastructure for the surface, marine, and aviation modes of passenger and freight transportation.
>
> Consideration will be given to the types and key features and qualities of metrics that can inform investments intended to increase the resilience of transportation system assets and their critical functions following natural disasters as well as for longer-range resilience planning for a wide array of natural hazards such as hurricanes, floods, wildfires, heat waves,

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[9] P.L. 116-94, Further Consolidated Appropriations Act, 2020, Division H—Transportation, Housing and Urban Development, and Related Agencies Appropriations Act, 2020, Title I, Department of Transportation, Office of the Secretary for Research and Technology, 133 Stat 2534, 2934, December 20, 2019. https://www.congress.gov/116/plaws/publ94/PLAW-116publ94.pdf.

> high winds, and changing freeze-thaw patterns. The kinds of data, methodologies, and analytic tools needed to design and apply such metrics will be examined as well as to evaluate their relevance and prioritize their use. Consideration will be given to metrics described in the literature and being used, developed, or recommended by federal agencies, state, tribal, and local governments, metropolitan planning organizations, and other public and private transportation practitioners.
>
> Based on the findings of this review, the committee will make recommendations, as appropriate, on how metrics can be developed, improved, and applied to make more informed decisions such as when to employ higher design and construction standards and when to increase investments overall to strengthen the resilience of transportation infrastructure and systems. The committee will give special attention to metrics that can be applied by Congress and other policy makers to inform decisions about when and how much to invest in transportation resilience, and how to design infrastructure funding programs that prioritize resilience.

STUDY SCOPE AND APPROACH

To conduct the study, the National Academies appointed an interdisciplinary committee of 12 members with expertise in multiple modes of transportation, transportation resilience management and analysis, economics, risk analysis, and decision-aid tools. Beginning with the study charge, as articulated in the Statement of Task, and in considering the legislative origins, the committee made several decisions about the study scope that shaped the study approach.

As the Statement of Task describes, Congress is looking at resilience from the perspective of making decisions about appropriating funds for upgrading transportation infrastructure to address natural disasters throughout the country. The decision to fund upgrades is relevant to infrastructure needing replacement, requiring restoration after a disaster, and being planned for new service. Upgrading can be accomplished through diverse actions, for instance by

- Building resilience into transportation infrastructure already in service, for example, by retrofitting bridge piers or adding restrainers to beams to protect against a potential earthquake that could threaten the structural integrity and functionality of the bridge;
- Rebuilding assets that are coming to the end of their life to upgraded standards that improve their resilience to natural disasters and climate change stressors;
- Rebuilding assets that are damaged by a natural disaster and stressors to a higher, more resilient standard;
- Adding to or improving networks to add redundancy;

- Relocating assets of a transportation network to sites with lower risk of stress and damage; or
- Enhancing design standards for new infrastructure to improve resilience to natural disasters and changing climate conditions.

The infrastructure for the U.S. highway system is largely owned by public agencies, for example, state departments of transportation and municipal governments, while services are provided by drivers and firms owning and operating their own vehicles to serve passengers and freight. On the other hand, railroads—and in some instances, mass transit systems—are vertically integrated, with the same entity owning and maintaining the infrastructure and delivering the services. While a state DOT or municipality may logically focus resilience planning on its infrastructure, vertically integrated service providers must consider all assets essential for delivering service. This underscores the importance of adopting a broad view of transportation services in resilience planning, including caring for and investing in physical assets and the skilled people to plan, operate, and maintain them; rolling stock; energy sources; and control systems. It also requires putting in place operating strategies appropriate to this purpose. In keeping with the legislative request for this study and the sponsor's charge, however, the committee focused its efforts on the state of practice and research literature aimed at making the major physical assets of the transportation modes and their networks (such as those assets listed in Table 1-1) more resilient to natural disasters and changing climate conditions.

The congressional statutory mandate for this study cites natural disasters, hazards, and other potential disruptions in broad terms, and the committee's definition of natural hazard includes not only significant acute weather and geophysical disturbances (e.g., hurricanes, earthquakes) but also longer-term (chronic) stressors (e.g., sea level rise, changing temperature and precipitation norms), some of which are exacerbated by climate change. This study commenced during the onset of the COVID-19 pandemic. Therefore, the committee considered early in its deliberations whether resilience to a pandemic should be included directly as a subject matter of the study and its recommendations. The study committee concluded, however, that it should focus on methods, tools, and measures that will help transportation decision makers determine which investments are needed to enhance the physical infrastructure's resilience, particularly with respect to the harm caused by natural disasters and stressors. Although pandemics are a natural hazard, they have few direct effects on the physical condition of transportation infrastructure. Resilience to pandemics, therefore, is not given direct attention in this report.

Because the measurement of resilience draws on concepts and practices developed in domains such as structural and geotechnical engineering,

TABLE 1-1 Physical Infrastructure Assets for Transportation Modes

Transportation Mode	Physical Infrastructure Assets[a]
Road network	Roads, bridges, tunnels, culverts, traffic signals, toll collection gantries/booths
Maritime	Docks, breakwaters, entrance channels, main basins, container yards, roads and rail lines, container freight terminals, warehouses
Air transportation	Airport terminals, runways, taxiways, control towers, aprons, hangars, access roads, heliports
Inland waterways	Channels, locks, dams, terminals
Railroad	Tracks, bridges, tunnels, culverts, yards, maintenance facilities, passenger stations, signal and traction power systems
Transit[b]	Tracks, bridges, tunnels, stations, signal and traction power systems, maintenance and storage facilities, bus roadways
Pipelines	Pipes, pumping stations, compressor stations, manifolds, storage facilities

[a] Various transport networks are also supported by systems with control, monitoring, and communications functions, as well as fire, life, safety, and security capabilities.

[b] Modes include, but are not limited to, bus, commuter rail, ferry, heavy rail, and light rail.

emergency preparedness, hazard mitigation, asset management, business continuity, and anti-terrorism security, the language used for defining and measuring resilience varies. As entities and industries have borrowed and adapted concepts to suit their specific needs, the same terms have come to mean different things in different contexts. This variability in terminology and definitions (e.g., the meanings of hazard, threat, vulnerability, risk, and criticality) can complicate efforts to reach and convey a common understanding of what is meant by resilience and how it can be analyzed, measured, and deliberately enhanced. As the recent National Cooperative Highway Research Program publication *Mainstreaming System Resilience Concepts in Transportation* notes, "The terminology of resilience, particularly when considering extreme weather/climate change, has in the past included usage of the terms 'vulnerability' and 'risk,' often interchangeably. The cross-pollination of these terms in the past has sometimes sown confusion in the transportation field."[10] Box 1-1 contains definitions of key terms and concepts as they are used in this report, recognizing that these definitions may not apply when the terms and concepts are used in other contexts.

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[10] NASEM (National Academies of Sciences, Engineering, and Medicine). 2021. *Mainstreaming System Resilience Concepts into Transportation Agencies: A Guide.* Washington, DC: The National Academies Press, p. 128. https://doi.org/10.17226/26125.

BOX 1-1
Definitions

Adaptive capacity—Ability of a system to adjust, repair, and respond to damage or disruption.[a]

Climate change—Changes in average weather conditions that persist over multiple decades or longer. It encompasses increases and decreases in temperature and changes to features of the climate systems, such as shifts in precipitation.[b]

Criticality—Importance or value of infrastructure asset, in terms of the cost to users, owners, and society from a loss in functionality.

Disruption—Degradation of system functionality due to a hazard.

Exposure—Whether an asset experiences a stressor.[c]

Natural hazard—A natural phenomenon that can produce damaging disruptions on systems and their functionality.[d]

Resilience—The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption.[e]

Risk—The potential for loss of functionality of a system from exposure to a hazard that exploits its vulnerability. The value or cost of that loss.[f]

Sea level rise—Increase in the volume—and thus, elevation level—of the world's oceans resulting from global warming.

There is a large body of research on resilience and resilience metrics but some disconnect between the research and practical applications, which, not surprisingly, lag behind the research. In its work, the committee examined both research and practice and worked to build connections between the two, with the focus on making recommendations about advancing the practice.

To learn about existing approaches to measuring the resilience of transportation infrastructure and how agencies approach investment decisions with resilience in mind, the committee held several information gathering sessions with panels of experts from a diverse set of transportation modes. They included experts in seaports, airports, inland waterways, railroads, highways, and regional planning. Among the regional, state, and federal agencies consulted were the Federal Highway Administration, FEMA, the U.S. Army Corps of Engineers, the Port of Long Beach, the San Diego

Sensitivity—Whether the asset may be damaged or disrupted by the stressor.[g]

Vulnerability—Potential for harm to system functionality due to disruption caused by a hazard. Vulnerability is a function of the characteristics—scale and scope—of the hazard and the location, design, and condition of the infrastructure asset.[h]

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[a] FHWA (Federal Highway Administration). 2015. "Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance." https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf.

[b] Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, eds. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.

[c] FHWA. 2015. "New Tool Helps Agencies Manage Transportation Assets in the Face of Climate Change." https://www.environment.fhwa.dot.gov/Pubs_resources_tools/publications/newsletters/feb15nl.pdf.

[d] NRC (National Research Council). 2012. *Disaster Resilience: A National Imperative.* Washington, DC: The National Academies Press. https://doi.org/10.17226/13457; NIST (National Institute of Standards and Technology). 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume 1.* NIST Special Publication 1190. http://dx.doi.org/10.6028/NIST.SP.1190v1.

[e] The White House. 2013. "Presidential Policy Directive 21: Critical Infrastructure Security and Resilience (PPD-21)."

[f] NRC. 2012. *Disaster Resilience: A National Imperative.* Washington, DC: The National Academies Press. https://doi.org/10.17226/13457; B.M. Ayyub, ed. 2018. *Climate-Resilient Infrastructure: Adaptive Design and Risk Management.* Manual of Practice 140. American Society of Civil Engineers.

[g] FHWA. 2015. "New Tool Helps Agencies Manage Transportation Assets in the Face of Climate Change." https://www.environment.fhwa.dot.gov/Pubs_resources_tools/publications/newsletters/feb15nl.pdf.

[h] NRC. 2012. *Disaster Resilience: A National Imperative.* Washington, DC: The National Academies Press. https://doi.org/10.17226/13457.

County Regional Airport Authority, several state DOTs, the New York Metropolitan Transportation Authority, and the Hampton Roads Transportation Planning Organization. The panelists are listed in the Preface and in Appendix B. The information gleaned from these panel discussions was invaluable to the committee in informing its deliberations that led to this report.

After this series of discussions with modal experts and transportation practitioners, the committee realized that any recommendations on input data and output metrics (or measures) relevant to the evaluation of transportation resilience would have limited utility in the absence of information on how to derive and apply them. To that end, the committee sought to identify approaches for measuring transportation asset resilience and the potential benefits conferred from strengthening it.

The committee carefully considered the feasibility of identifying a single or small set of metrics to characterize the resilience of transportation systems and services. It quickly became apparent that such a unitary metric was unlikely to be found. Among the elements contributing to this determination are the following:

- Transportation itself is a complex combination of infrastructure, processes, and people that delivers many different services and functionalities.
- Transportation operates in many highly varied contexts, across which threats from natural hazards, demand for services, and demographic and environmental conditions range widely.
- Transportation assets comprise a broad range of infrastructure types, scales, ownership, and management patterns.

While it is possible to measure the resilience of aspects of particular facilities and services in the face of specific hazards, aggregating across systems, services, hazards, and contexts to produce a singular or small set of metrics for a system or region is unlikely, a conclusion supported by the committee's review of both the state of the practice and contemporary research.

While measuring transportation resilience at any reasonable scale—community, state, or nation—is beyond the reach of practical tools, the committee found that it is possible to create a decision framework that would inform decisions about investments in transportation resilience. Such a framework considers characteristics of transportation assets, their vulnerability and criticality, and the natural hazards they are likely to face. This framework provides a series of analytical steps and suggested metrics for measuring resilience benefits in a logical and consistent manner so they can be weighed against the costs incurred to achieve them.

The primary product of this report, therefore, is a framework for measuring resilience benefits in a logical and consistent manner so they can be weighed against the financial outlays and other costs likely to be incurred to achieve them. The committee envisions that such a resilience analysis framework would be part of the overall decision calculus for transportation infrastructure investments.

REPORT ORGANIZATION

The remainder of this report is organized into five chapters as follows:

- Chapter 2 provides background about common natural hazards and climate change in the United States and, within that context, an example of the effects that such disruptions can have on major transportation facilities and systems. The chapter also relates the way natural hazards can be characterized for analysis purposes and describes several tools that historically have been used by transportation planners to understand the natural hazards affecting their facilities. Chapter 2 thus provides important context for evaluating resilience.

- Chapter 3 explores the current state of practice for evaluating resilience of transportation facilities and systems and evaluating resilience-related investments. It includes a variety of examples of resilience analyses, and it concludes with an overview of the metrics practitioners are using for resilience planning.
- Chapter 4 reviews resilience analysis approaches and metrics in the research literature.
- Based on the information about the state of practice and research, Chapter 5 offers a multi-step framework to provide decision makers with a general methodology for evaluating candidate actions to best increase the resilience of at-risk transportation facilities. The chapter also presents a portfolio of input data and output measures for use during the various steps of the framework.
- Chapter 6 presents the study recommendations and their rationales.

2

Natural Hazards, Climate Change, and America's Transportation Infrastructure

The increasing threat that natural hazards pose to the nation's transportation infrastructure and mobility varies by region and by mode. To boost transportation resilience, policy makers and infrastructure decision makers need a solid understanding of the specific hazards that the transportation systems under their purview face. Resilience analysis must therefore begin with evaluations of these hazards, paying special attention to the most acute and severe events—commonly called disasters—but also accounting for the effects of changing environmental conditions such as from climate change.

Natural disasters, and their accompanying economic losses, are on the rise. The United States experienced a record-breaking 22 billion-dollar natural disasters in 2020, according to the National Oceanic and Atmospheric Administration (NOAA).[1] Hurricane Laura, the California wildfires, and the Midwestern derecho[2] were the leading contributors to the $95 billion in losses. During the 1980s, billion-dollar events, even after adjustments

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[1] NOAA's calculations of billion-dollar events are adjusted for inflation. See NOAA NCEI (National Centers for Environmental Information). 2021. "U.S. Billion-Dollar Weather and Climate Disasters." https://doi.org/10.25921/stkw-7w73.

[2] The National Weather Service describes a derecho as "a widespread, long-lived wind storm that is associated with a band of rapidly moving showers or thunderstorms. Although a derecho can produce destruction similar to the strength of tornadoes, the damage typically is directed in one direction along a relatively straight swath. As a result, the term 'straight-line wind damage' sometimes is used to describe derecho damage. By definition, if the wind damage swath extends more than 240 miles (about 400 kilometers) and includes wind gusts of at least 58 mph (93 km/h) or greater along most of its length, then the event may be classified as a derecho." See https://www.weather.gov/lmk/derecho.

for inflation, averaged only 2.9 per year. By the 2010s, the average reached $11.9 billion in disasters per year.

Transportation agencies are on the front lines when natural disasters of all sorts strike. In the wake of the 2020 derecho, the Iowa Department of Transportation (DOT) sent crews from 50 garages to haul tens of thousands of loads of debris.[3] In January 2021, the nation watched, transfixed, as Caltrans released drone footage of Big Sur's Highway 1, wiped out in a flood at Rat Creek. Vegetation that resisted erosion had been destroyed in 2020's Dolan Fire.[4] The Rat Creek washout, although the most devastating after the Dolan Fire, was one of 50 landslides on the highway requiring cleanup and repair.

The impacts of hurricanes often ripple across wider freight markets and supply chains. In addition to direct damage disrupting service, freight capacity—including trucking and at ports—can be diverted to emergency relief. Hurricane Laura disrupted freight service by damaging the rail network around Lake Charles, Louisiana.[5] When an unprecedented hurricane struck the coast of California in 2014, the Port of Long Beach saw operations at a standstill for days, and it took several months for the nearby roads and facilities to be fully restored.[6] Hurricane Harvey's tremendous rainfall disrupted most road travel for days, but emergency preparedness efforts among the public sector, industrial sectors, and the Port of Houston prevented, one study concluded, what "could have been some major problems that could have devastated local, regional, and even national supply chains."[7]

Modeling conducted for the Fourth National Climate Assessment indicates that the increasing danger from natural hazards will be a long-term trend due to increasing emissions and atmospheric concentrations of

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[3] Iowa DOT (Department of Transportation). 2020. "Iowa DOT Answers the Call for Debris Removal Following Devastating Derecho." *Transportation Matters for Iowa*, August 27. https://www.transportationmatters.iowadot.gov/2020/08/iowa-dot-answers-the-call-for-debris-removal-following-devastating-derecho.html.

[4] Alexander, K. 2021. "Highway 1 Through Big Sur Will Be Repaired." *San Francisco Chronicle*, February 10. https://www.sfchronicle.com/environment/article/In-Big-Sur-rain-came-down-and-so-did-Highway-1-15938072.php.

[5] Straight, B. 2020. "Rail Service Still Hampered, But Truck Stops, Roadways Reopened Following Hurricane Laura." Freight Waves, August 29. https://www.freightwaves.com/news/rail-service-still-hampered-but-truck-stops-roadways-reopened-following-hurricane-laura.

[6] Port of Long Beach. 2016. *Climate Adaptation and Coastal Resiliency Plan.* https://www.slc.ca.gov/wp-content/uploads/2018/10/POLB.pdf.

[7] NASEM (National Academies of Sciences, Engineering, and Medicine) 2020. *Strengthening Post-Hurricane Supply Chain Resilience: Observations from Hurricanes Harvey, Irma, and Maria.* Washington, DC: The National Academies Press, p. 28. https://doi.org/10.17226/25490.

greenhouse gases.[8] For roads, both the Assessment's high-emission and low-emission scenarios show increased costs, cumulatively up to an additional $230 billion through 2100, just to repair damage attributed to changes in temperature, precipitation, and freeze-thaw cycles. For bridges, the primary danger is scour, where the flow of water undermines the integrity of the bridge piers. Under the high-emission scenario, 4,600 road bridges will be vulnerable in 2050 and 6,000 in 2090. Even in the low-emission scenario, 5,000 bridges will be vulnerable in 2090. For rail, extreme heat threatens to delay freight and passenger trains alike.[9] Cumulative costs of increased railroad delays through 2100 are $50 billion in the high-emission scenario and $40 billion in the low-emission scenario.[10]

Whether a hazard causes harm depends on the characteristics of the infrastructure and a society's preparation and ability to respond. Resilience analysis, planning, and management require an understanding of natural hazards and climate change effects, including their likelihood and characteristics. Transportation agencies that analyze natural hazards use a range of methods from qualitative descriptions to quantitative probabilistic models. All of these methods must accommodate the reality that while natural hazards are a fact of life, there is still a great deal of uncertainty about where, when, and how the next natural hazard will strike.

This chapter provides an introduction to natural hazards, a description of how some are affected by climate change, and a discussion of the impacts of both on transportation. The chapter begins with an explanation of why an understanding of natural hazards—their likelihood and characteristics—is key to building resilience. The chapter provides a brief overview of how meteorological, geological, and climate change–related hazards affect transportation in the United States, including how they vary by region and location. To lay the groundwork for resilience metrics, the chapter then reviews the basics of measuring hazard likelihood, the aspects that go into hazard characterization, and the approaches used to develop hazard scenarios that can be integrated into resilience analysis. The chapter

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[8] Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, eds. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.

[9] Extreme heat causes the steel in rails to expand and buckle, causing trains to derail. Extreme cold causes the steel to contract and crack, similarly causing derailments.

[10] Cumulative costs are in addition to a base calculated from 1950 to 2015, in 2015 dollars, and discounted 3% annually. See EPA (U.S. Environmental Protection Agency). 2017. *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment*. EPA 430-R-17-001. Washington, DC: U.S. Environmental Protection Agency, pp. 74–99.

concludes with a discussion of the role of federal investment in providing data for hazard modeling and projections.

TO BUILD RESILIENCE—FIRST, UNDERSTAND THE HAZARD

All approaches to evaluating resilience to inform transportation investment decisions require knowledge of the natural hazards. Because natural hazards vary across the landscape and in their interaction with transportation modes, transportation agencies are often required to conduct individualized analysis of relevant hazards and their likely effects. Climate change compounds the difficulty of analyzing hazards because the analysis can no longer assume that the forces that produce the natural hazards are stable. Climate change also introduces shifts to normal environmental conditions, which must also be taken into account. The importance of understanding hazards is exemplified by Step 1, "Explore Hazards," of the U.S. Climate Resilience Toolkit's advisor on Steps to Resilience.[11] The word "explore" communicates that best practice is not just to jump into the most detailed analysis possible to build a comprehensive list of all conceivable hazards. Instead, Step 1 includes "investigate regional climate" and "understand exposure." Hazard analysis typically searches for significant hazards and for infrastructure assets that are most vulnerable to damage and disruption. The toolkit pulls together resources from across the federal government that can aid in identifying the potential natural hazards or climate changes for a given region or community.

The analysis of natural hazards focuses on two separate but interrelated questions, both of which wrestle with uncertainty. One inherent feature of natural hazards is that while we know, generally, that they will occur, we do not know specifically where, when, and how severe the effects will be. First, how likely is a specific natural hazard? In the near term? In the long term? For long-lived infrastructure, this question is often stated as follows: How likely is it over the design life of the asset? The second question delves into the interaction between the natural hazard and transportation. If a natural hazard event were to occur, what are the likely effects that will impact transportation assets and functions? The description and analysis of hazard likelihood and effects is called hazard characterization. Both the likelihood and the other characteristics of hazards are necessary inputs to the resilience analysis methods and metrics discussed more fully in Chapters 3, 4, and 5.

Hazard characterization also requires comprehensive knowledge of the potentially affected infrastructure assets, including their location, type, function, condition, and maintenance history. Therefore, asset management

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[11] U.S. Climate Resilience Toolkit. n.d. "Steps to Resilience." https://toolkit.climate.gov/#steps.

programs, which develop and utilize this knowledge, are vital for integrating resilience into transportation decision making. Asset management is a strategic and systematic process of operating, maintaining, and improving physical assets. Best practices in asset management rely on both engineering and economic analyses, employing high-quality information to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost.[12]

NATURAL HAZARDS AND CLIMATE CHANGE

Natural hazards that typically affect transportation in the United States are listed in Table 2-1. To understand the impact of climate change, it is helpful to divide the hazards into meteorological (acute), geological, and climate change–related (chronic) hazards.

TABLE 2-1 Types of Natural Hazards[13]

Meteorological Hazards	Geological Hazards	Climate Change–Related Hazards
Avalanche	Earthquake	Precipitation: changes in averages, extremes, and seasons
Debris flow	Land subsidence	
Drought	Landslide and rockfall	
Fire/wildfire	Sinkhole	Temperature: changes in averages, extremes, and seasons
Flood/flash flood	Tsunami	
Hail	Volcanic eruption	
Heavy rain		Sea level rise
High wind		
Ice flow		Interaction of precipitation, temperature, and sea level changes with other meteorological hazards
Lightning		
Mudflow		
Snow		
Storm surge		
Tornado		
Tree fall		
Tropical cyclone		
Water table changes		

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[12] MAP-21 (Section 1103(a)(2)).

[13] Zaghi, A.E., J.E. Padgett, M. Bruneau, M. Barbato, Y. Li, J. Mitrani-Reiser, and A. McBride. 2016. "Establishing Common Nomenclature, Characterizing the Problem, and Identifying Future Opportunities in Multihazard Design." *Journal of Structural Engineering* 142(12). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001586.

Meteorological Hazards

Meteorological hazards are commonly called bad weather: hurricanes and other storms with high winds, heavy rain or snow, and intense lightning; heat waves and severe cold snaps; and drought. High winds can occur during major storms such as hurricanes and nor'easters, as well as more localized windstorms such as tornadoes. Heavy winds can destroy transportation structures and facilities, cause injuries and fatalities to people, and topple trees leading to power outages and blocked roads and rail lines. In coastal areas, high winds generate storm surges that can cause flooding. Wind and storm surge can also accelerate coastal erosion, undermining infrastructure. Chlorides from salt water can also intensify corrosion of some infrastructure assets and thus impair their durability and performance in the long term. Rain can cause mudslides and flooding, while snow can block roads and other transportation infrastructure. The combination of high winds and heavy snow can cause a "white-out" condition that reduces visibility and can cause vehicle collisions and other damage. Lightning can damage structures, particularly electric power lines and signaling systems, and can also cause trees to fall and block roads and tracks. Lightning can also ignite wildfires, the severity of which can be worsened by drought. As will be discussed later in this chapter, meteorological hazards can occur simultaneously or in overlapping succession.

Geological Hazards

Geological hazards include earthquakes, tsunamis, volcanic eruptions, landslides, and land subsidence. Earthquakes cause injuries, fatalities, and severe damage to transportation facilities not built to withstand them. Tsunamis following earthquakes create damage from both the force of wave action and flooding. Volcanic eruptions cause structural damage from lava flows, gas emissions, and hot cinders that can ignite fires. Landslides, including rockfalls, endanger personal safety and can close transportation routes. They can be triggered by heavy precipitation (e.g., in mudslides) and other meteorological events. Land subsidence typically causes more slow-acting damage. As land sinks, transportation infrastructure may become flooded.

Climate Change–Related Hazards

Climate change contributes to natural hazards by increasing average temperatures and altering historic patterns of extreme temperatures and precipitation. These changes in atmospheric conditions can potentially affect any meteorological hazard. Specific hazards include sea level rise, periods of extreme heat or cold, and changes in freeze-thaw patterns, including melting permafrost.[14] These chronic changes in the natural environment, which are happening today and are expected to be exacerbated by climate change, can alter the context under which transportation operates. Such hazards may affect transportation directly or they may interact with meteorological and geological events, affecting their frequency and severity. To the extent that transportation networks have been designed using norms derived from historical weather data, they are likely to be unprepared to withstand these climate change impacts.

Sea level rise leads to repeated nuisance flooding, increases the height of high tides, and may also raise the water table beneath coastal land and possibly destabilize landforms. In many coastal communities, roads are located at a lower elevation than the surrounding lands to allow water to drain into the streets and away from homes and businesses. Rail lines follow waterways to reduce grades. As sea level rises, local drainage systems become less effective, causing increased flooding on low-lying roads and costly delays to the transportation system. More than 7,500 miles of roadway on the Eastern seaboard are located in high tide flooding zones.[15]

Sea level rise may also be a hazard to airports, which are commonly built along tidal waters. Railroads in coastal regions often cut across marsh areas and run along the coastline as well. Sea level rise may also reduce the clearance under bridges, affecting or blocking navigation. A rise in the water table can flood tunnels, including their entrances and vents, and other infrastructure that is below grade. Tunnels, especially rail transit tunnels, may be vital links for communities and travelers with few other travel options. All of the effects of sea level rise can be compounded by increased rainfall intensity triggered by climate change.[16]

As the case of Devils Lake in North Dakota demonstrates, increasing water levels do not only affect coastal communities and their transportation infrastructure. The increase in precipitation over the past 80 years has had a dramatic effect on the water level in the lake, because it has no natural

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[14] The base layer of roads can expand, contract, and shift during freeze-thaw temperature cycles, causing the surface to crack. Increases in the number of freeze-thaw cycles during the winter season because of climate change may more quickly degrade the quality of road surfaces. See EPA. 2017. *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.* EPA 430-R-17-001. Washington, DC: U.S. Environmental Protection Agency, pp. 79–81.

[15] Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, eds. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.

[16] The content in this paragraph draws from Titus, J. 2002. "Does Sea Level Rise Matter to Transportation Along the Atlantic Coast?" https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/united-states/east-coast/regional---us-east-coast/Titus.-2002.-US-Transportation--SLR-on-the-Atlantic-Coast.pdf.

outlet. Since 1964, the water level of the lake has risen by 13 meters, the area of the lake has expanded by 10 times, and the volume of water in the lake has expanded by 32 times. As a result, local farms have been flooded, the local towns have been protected by levees, and highways and key rail lines for freight and passenger train service have been washed out.[17]

In the United States, high temperature records over the past two decades far exceed the number of low temperature records.[18] Recent data from NOAA indicate that a warming pattern occurred in all of the contiguous United States with the exception of portions of the Upper Midwest and Northern Plains (see Figure 2-1).[19] Nonetheless, changes in temperature patterns—extreme hot as well as extreme cold—can affect infrastructure assets and the experience of employees and customers. The 2021 polar vortex that affected the south-central United States had a severe effect on energy infrastructure, caused an estimated $200 billion in economic losses, and, as SwissRe reports, "is on track to rival and perhaps even surpass the likes of intense climate disasters more well acquainted to the state such as Hurricane Harvey (2017) and Ike (2008)."[20] Extreme temperatures can cause health emergencies for employees and customers exposed to the elements. Extreme heat can melt asphalt on roads and airport tarmacs. For rail infrastructure, extreme heat can lead to track buckling and extreme cold can cause brittle fracture of track. Changes in freeze-thaw patterns can affect the life span and maintenance needs of roads and runways. Changes in temperature patterns are a particular concern for all types of transportation infrastructure and facilities in Alaska. When permafrost thaws, land in the melted area subsides.[21]

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[17] Larson, D. 2012. "Runaway Devils Lake." *American Scientist* 100(1):46. https://www.americanscientist.org/article/runaway-devils-lake.

[18] Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, eds. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.

[19] NOAA. 2021. "NOAA Delivers New U.S. Climate Normals." https://www.ncei.noaa.gov/news/noaa-delivers-new-us-climate-normals.

[20] Pui, A., and S. Horie. 2021. "Polar Vortex: A Counter Intuitive Threat of Climate Change?" SwissRe Corporate Solutions, April 13. https://corporatesolutions.swissre.com/insights/knowledge/polar-vortex-a-counter-intuitive-threat-of-climate-change.html.

[21] EPA. 2017. *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment.* EPA 430-R-17-001. Washington, DC: U.S. Environmental Protection Agency, pp. 100–107.

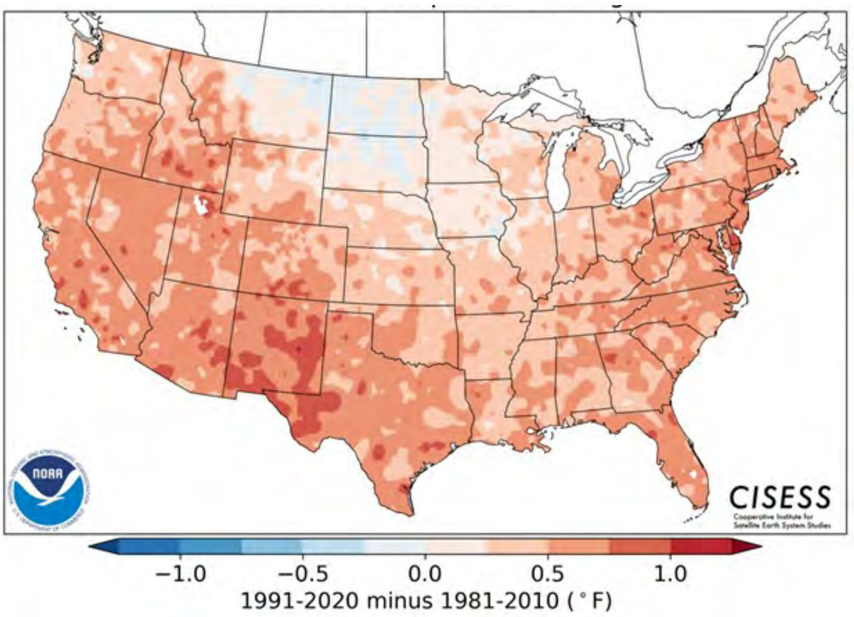

FIGURE 2-1 Average annual temperature change for the contiguous United States from the 1981–2010 climate normals to the newest data in the 1991–2020 normals.[22]

Hazards Vary by Region and Location

Meteorological and geological hazards and the effects of climate change vary by region and location. Resilience analysis, planning, and management processes need to account for this variation.

In the United States, it is generally well understood that the country's diverse regions experience different mixes of natural hazards. Transportation agencies adopt practices adapted to these regional circumstances. Hurricanes are tropical cyclone storms that form in the North Atlantic and North Pacific, affecting shipping and bordering coastal regions, and they commonly traverse far inland to cause damage far from coasts. Storm surge from high winds is confined to areas bordering large bodies of water. Wildfires are typically the most dangerous on the West Coast and in the Rocky Mountain region but also occur in the south-central and southeastern states. Tornadoes occur frequently in the central plains, Florida, and the Gulf Coast states. Severe thunderstorms capable of producing tornadoes

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[22] NOAA. 2021. "NOAA Delivers New U.S. Climate Normals." https://www.ncei.noaa.gov/news/noaa-delivers-new-us-climate-normals.

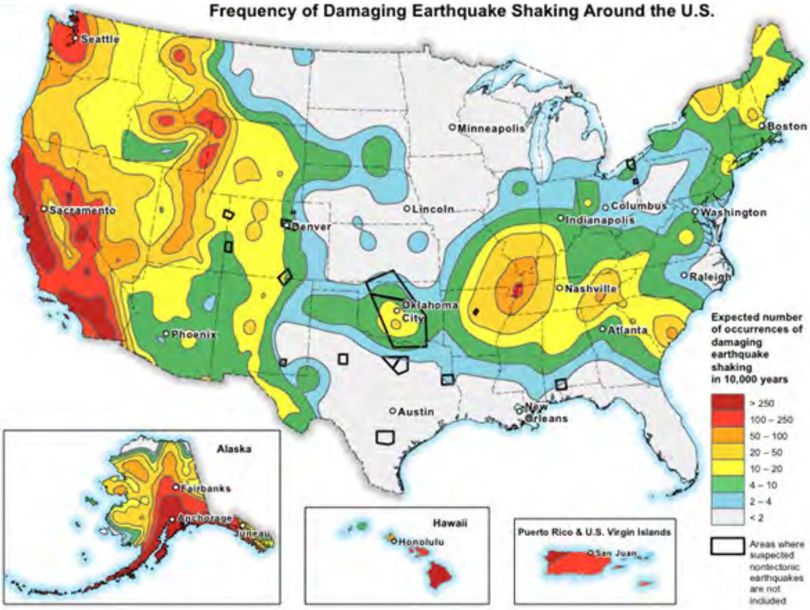

FIGURE 2-2 Expected frequency of earthquake occurrences in the United States.[23]

and hail appear in every state. Mountainous regions create the conditions for landslides and rockfalls. For earthquakes, the highest hazard areas are in Alaska, Hawaii, Puerto Rico, the West Coast, and a small region in the central United States (see Figure 2-2).[24]

Similarly, the significance of flooding will vary by both the region and the specific locations of infrastructure assets. The significance of flooding will also vary by the type of flood, such as flash floods with little warning, storm surges from cyclones and tsunamis, hurricane driven rain, or snow melt. Figures 2-3 and 2-4 present the historical flood risk in New York and California, respectively. The maps were generated using NOAA's

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[23] USGS. n.d. "Introduction to the National Seismic Hazard Maps." https://www.usgs.gov/natural-hazards/earthquake-hazards/science/introduction-national-seismic-hazard-maps?qt-science_center_objects=0#qt-science_center_objects.

[24] NOAA. n.d. "National Centers for Environmental Information." https://www.ncei.noaa.gov; USGS (U.S. Geological Survey). n.d. "Earthquake Hazards." https://www.usgs.gov/natural-hazards/earthquake-hazards.

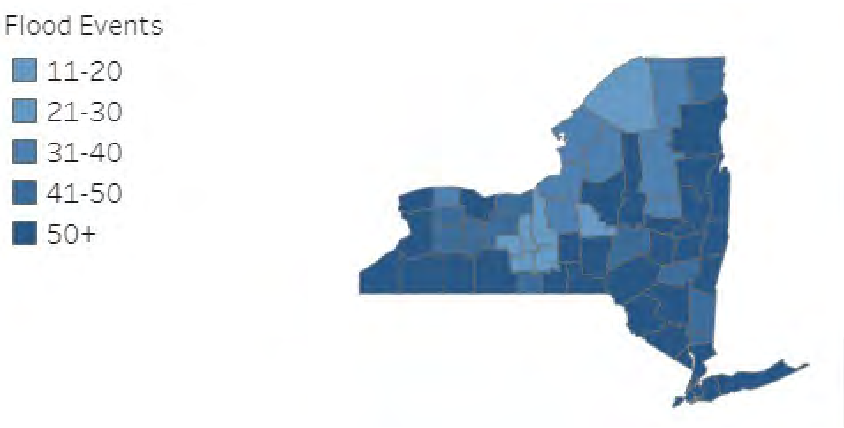

FIGURE 2-3 Number of flood events reported for a county or zone in New York 1996–2019.[25]

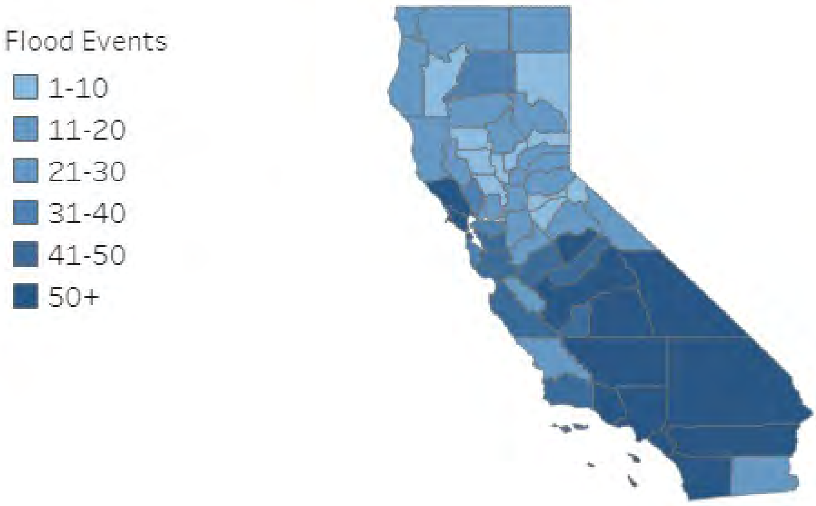

FIGURE 2-4 Number of flood events reported for a county or zone in California 1996–2019.[26]

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[25] FEMA. 2021. "Historical Flood Risk and Costs." https://www.fema.gov/data-visualization/historical-flood-risk-and-costs.

[26] FEMA. 2021. "Historical Flood Risk and Costs." https://www.fema.gov/data-visualization/historical-flood-risk-and-costs.

interactive data tool, which presents historical flood risk using data from 1996 to 2019.[27]

Increases in the Frequency of Extreme Weather Events

Climate change can lead to shifts in extreme weather, and trends indicate that large areas of the United States are being subject to such extremes. Because conventional design, material, and operational standards in transportation are built around historic weather data, increases in the likelihood of a hazard can turn a distant threat into an imminent disaster. NOAA's climate extreme index tracks changes in extremes for the contiguous United States and its regions. The index consolidates extremes in temperature and precipitation (i.e., days when temperature or precipitation are in the top or bottom 10% of the historical average) and is reported as a percentage of the total number of days for the region. Going back more than a century, on average, 21% of the United States experiences extremes in any given year. Over the past 20 years, however, this average has risen to 28%. Regionally, increases in the average area affected by extremes over the past 20 years range from a low of 1.5 percentage points in the Northwest to a high of 13.7 percentage points in the Northeast. In terms of years above the long-run average, the Ohio Valley ranks first, with 15 out of the past 20 years above the long-run average. The trend in extremes may be accelerating. Over the past 5 years, only four of the nine regions experienced any single year below the long-run average for extremes.[28]

EXPOSURE AND EVENT LIKELIHOOD

Evaluating resilience to natural hazards starts with exposure. Because the likelihood of natural hazards varies by region and location, the first pass at a comprehensive analysis of exposure can be a simple question of whether a particular hazard ever occurs in a particular location. The next level of analyzing exposure is to categorize the hazards on a scale from low to high likelihood of occurrence. However, quantitative analyses of resilience typically require describing the likelihood of a natural hazard as a specified event with a defined probability. For example, the Federal Emergency

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[27] FEMA (Federal Emergency Management Agency). 2021. "Historical Flood Risk and Costs." https://www.fema.gov/data-visualization/historical-flood-risk-and-costs.

[28] The four regions with at least 1 year below the long-run average from 2016 to 2020 are Rocky Mountains and Northern Plains (2 years), Southwest (1 year), West (1 year), and Northwest (3 years). Study committee analysis of Climate Extremes Index data; contiguous United States and regional Climate Extremes Index averages from 1910–2020 and 2001–2020 were compared. See NOAA. n.d. "U.S. Climate Extremes Index (CEI)." https://www.ncdc.noaa.gov/extremes/cei.

Management Agency (FEMA) defines a "base flood" as "a flood having a one percent chance of being equaled or exceeded in any given year." FEMA's base flood also has a metric for flood elevation.[29]

Measuring Likelihood

Measuring likelihood is an integral step to producing the scenarios required for most approaches to resilience analysis. Metrics that capture hazard likelihood usually require data on past frequency and projections of future frequency. The first step is to turn a natural hazard into something that can be counted, usually defined as an "event." Measures of occurrence, and thus frequency of events, differ for different hazards. For example, the likelihood of floods is usually measured in annual probabilities, but the frequency of earthquakes is reported in events over 10,000 years.[30]

In addition, measuring frequency typically requires threshold values of severity to indicate when the magnitude of an event is sufficiently great to make it count as a hazard event. For example, for Atlantic hurricanes there are thresholds for named storms and for five categories indicating increasing severity. Earthquakes and tornadoes also have measurement scales that categorize events by severity. As knowledge about natural hazards improves, the categories and scales used to define thresholds for events are periodically revised.[31]

Comprehensive approaches to resilience analysis and planning require a way to put the likelihood of all hazards on the same frequency scale. The National Institute of Standards and Technology (NIST), in its guide for community resilience, advises using three categories: routine, design, and extreme. NIST uses a 50-year analysis period. The routine level is for hazards that have a 50% or greater probability of occurring over the next 50 years. The design level specifies the event with a 10% chance of happening over 50 years, and the extreme level events have a probability of 2–3% over 50 years. For earthquakes, NIST's extreme level is typically called the "maximum considered event." (For comparison, FEMA's base flood of 1% annual probability would have a roughly 40% chance of occurring over

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[29] FEMA. n.d. "National Flood Insurance Program Terminology Index." https://www.fema.gov/flood-insurance/terminology-index.

[30] USGS. n.d. "Introduction to the National Seismic Hazard Maps." https://www.usgs.gov/natural-hazards/earthquake-hazards/science/introduction-national-seismic-hazard-maps?qt-science_center_objects=0#qt-science_center_objects.

[31] The Weather Channel. 2020. "The Enhanced Fujita Scale: How Tornadoes Are Measured." https://weather.com/storms/tornado/news/enhanced-fujita-scale-20130206; USGS. n.d. "Moment Magnitude, Richter Scale." https://www.usgs.gov/faqs/moment-magnitude-richter-scale-what-are-different-magnitude-scales-and-why-are-there-so-many?qt-news_science_products=0#qt-news_science_products.

50 years.) Furthermore, each level is tied to a performance goal. Routine hazards should lead to minimal disruptions. The design hazard should be built into building and construction standards. Planning for the extreme hazard event should protect life but may require rescue and a significant recovery period.[32]

Defining the relevant event for measuring frequency may also depend on the technology operated by a transportation agency. For example, the Washington Metropolitan Area Transit Authority (WMATA) operates both heavy rail and bus service. For metrorail, even the rail lines above ground can support close to normal service in up to 6 inches of snow. Only increases in the frequency of snow events above 6 inches would worsen the resilience of WMATA's rail service. WMATA's bus service, however, is dependent on roads maintained by others. Bus routes may begin to be detoured or cut back with as little as 2 inches of snow.[33]

Likelihood with Climate Change

Measuring likelihood should also incorporate the effects of climate change. However, measuring changes in likelihood is also not a straightforward exercise. For example, the Atlantic hurricane season in 2020, breaking the record set in 2005, produced 30 named storms, and 2020's 13 hurricanes and 6 major hurricanes exceeded the average. 2020 was also the fifth consecutive year with an above average number of named storms.[34] Still, the era of good data on tropical cyclone storms begins only in the 1980s. Climate change could be affecting the frequency of all named storms or the intensity of major hurricanes or both. In addition, climate change may be affecting where major storms intensify, changing the frequency for some locations but not others. Similarly, for severe thunderstorms producing tornadoes, trends since the 1970s indicate a reduction in the number of days with at least one tornado but increases in the number of days with outbreaks of a large number of tornadoes. Climate change models predict continued increases in the number of severe thunderstorms in the Midwest and Great Plains states, especially in March, April, and May.[35]

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[32] NIST. 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume 1*. NIST Special Publication 1190. http://dx.doi.org/10.6028/NIST.SP.1190v1.

[33] WMATA. n.d. "Rail Snow Service." https://www.wmata.com/rider-guide/weather/rail.cfm; WMATA. n.d. "Bus Snow Service." https://www.wmata.com/rider-guide/weather/bus/index.cfm.

[34] NOAA. 2020. "Record-Breaking Atlantic Hurricane Season Draws to an End." https://www.noaa.gov/media-release/record-breaking-atlantic-hurricane-season-draws-to-end.

[35] USGCRP (U.S. Global Change Research Program). 2017. "Chapter 9: Extreme Storms" in *Climate Science Special Report: Fourth National Climate Assessment*. https://science2017.globalchange.gov/chapter/9.

Examples of Measuring Exposure and Likelihood

The U.S. Department of Transportation's (U.S. DOT's) Vulnerability Assessment Scoring Tool (VAST), which includes tools to analyze exposure to natural hazards, acknowledges that location-specific modeling incorporating climate change is the best way to produce projections for the likelihood of a natural hazard event. Tools are available that make the output of the climate change models useful at a local scale for transportation planning. For example, U.S. DOT's Climate Model Intercomparison Project (CMIP) Climate Data Processing Tool uses statistical methods to produce projections of changes in temperature and precipitation, including extreme heat and rainfall. The tool produces projections for changes in environmental conditions that then need to be integrated into models projecting the likelihood of meteorological and geological hazards.[36]

If models such as CMIP are not available, VAST offers indicators that transportation agencies can use to score an asset's exposure to a natural hazard. For storm surge, for example, the tool's indicator library provides a scale for scoring exposure based on miles from the coastline and elevation. The scores, from 1 to 4, do not represent probabilities but rather indicators that allow for comparing the relative exposure of different assets.[37]

The National Cooperative Highway Research Program report *Mainstreaming System Resilience Concepts into Transportation Agencies: A Guide* also provides step-by-step guidance on how to conduct an assessment of a transportation agency's exposure to natural hazards.[38]

Minnesota DOT, recognizing that its current infrastructure and practices already take into account past patterns of hazards, frames its evaluation of hazard likelihood in terms of the change expected over the next 20 years. Heavy precipitation leading to flooding and warmer winters received "very high" ratings for likelihood of worsening over the next 20 years. Vegetation patterns received a "high" rating for likelihood of change, leading to concerns about vegetation loss and invasive species causing soil erosion and wetland failure. On the other hand, wildfires and severe wind received "low" likelihood of change ratings.[39]

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[36] FHWA (Federal Highway Administration). n.d. "Climate Change Adaptation Tools: CMIP Climate Data Processing Tool." https://www.fhwa.dot.gov/environment/sustainability/resilience/tools.

[37] FHWA. n.d. "Climate Change Adaptation Tools: Vulnerability Assessment Scoring Tool." https://www.fhwa.dot.gov/environment/sustainability/resilience/tools. A further discussion of VAST will be found in Chapter 3 of this report.

[38] NASEM. 2021. *Mainstreaming System Resilience Concepts into Transportation Agencies: A Guide.* Washington, DC: The National Academies Press. https://doi.org/10.17226/26125.

[39] Meek, J. 2020. "MnDOT Transportation Resilience." Presentation to the Committee on Transportation Resilience Metrics, June 26.

HAZARD CHARACTERIZATION

The significance of a natural hazard depends not only on how likely it is to occur but also on how serious and widespread its effects are likely to be. Resilience analysis, therefore, must also incorporate knowledge about how specific natural hazards interact with specific transportation assets (including nodes, networks, and systems). Damage to infrastructure and facilities may not be the only important effect of a natural hazard. Essential personnel unable to report to work may also disrupt service. Failures in power supplies, water services, or communication technologies can affect entire systems. For intermodal nodes, damage to one mode can force closures of services on other modes, such as maritime and surface freight operations at a port or connecting transportation modes at a station, port, or airport.

To be able to assess the potential for damage or disruption, resilience assessment must first develop qualitative and quantitative descriptions of the loading (or stress) that the natural hazard puts on infrastructure assets. Physical forces such as the speed of the wind, the height of the flood, the type of debris flow, the amount of rain, or the number of days of extreme heat or cold are analyzed. Some of the categories and scales used to define hazard events, such as for hurricanes and tornadoes, already integrate knowledge about likely damage.

Hazard characterization describes the geographic distribution of loading intensity (or stress) generated by one or more natural hazard events. In addition to likelihood, hazard characterization includes the effects that directly cause damage and disruption and also must account for differences in the duration and scale of natural hazard events. Methods for hazard characterization vary from general descriptions of common hazards to detailed quantitative models of the specific effects on assets. Even general descriptions can still be useful for formulating mitigation strategies and plans. Case studies and historical patterns can also help characterize specific hazards.

Affected Area or Region

Hazard characterization also requires an analysis of the geographic area affected by the hazard event, which should be as spatially explicit as possible. Spatial analysis includes identifying specific locations for damage and the larger areas or regions affected by the damage and disruption. Again, different hazards have different conventions for measuring the area affected. For earthquakes, the load effect is often described in terms of the joint occurrence of shaking intensity over the region of interest.[40]

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[40] Jayaram, N., and J.W. Baker. 2010. "Efficient Sampling and Data Reduction Techniques for Probabilistic Seismic Lifeline Risk Assessment." *Earthquake Engineering & Structural Dynamics* 39(10):1109–1131.

For flooding or storm surge, spatial analysis usually focuses on the area inundated and the depth of the water.[41] Spatial analysis of hazard effects also must include the geographic extent of the transportation system under study and capture disruption to nodes and network links, as well as infrastructure assets.

Duration of the Hazard Event

Hazard characterization includes the entire arc of time from first warning to when the event is no longer actively producing effects. Analysis of duration focuses on the evolution of the loading intensity or effects of the hazard over time. For earthquakes, although the hazard may be active for just seconds to a minute, the duration and intensity of shaking (as well as potential aftershocks) are still critical to understanding the extent of damage. Post-event recovery from a damaging earthquake also requires a considerable amount of time; for example, the transportation system of San Francisco was impacted for several years after damage from the Loma Prieta earthquake.[42] For floods, wildfires, hurricanes, heat waves, and cold waves, the hazard event may be active for days to weeks. For flooding, the time required for water levels to subside, for example, significantly affects post-event recovery and thus needs to be part of characterizing duration. For chronic natural hazards associated with climate change, such as sea level rise or changing temperature and precipitation patterns, the duration is likely to be indefinite.

Forecasting

Hazard characterization includes the ability to forecast an event in a way that provides information on specific time and place and thus allows for taking temporary actions to reduce damage and save lives. Hurricane forecasting, for example, has advanced to the point that warnings go out 3–4 days in advance, advising that specific locations are likely to experience certain levels of intensity. Disaster preparations start ahead of hurricane landfall: windows are boarded up, sandbags positioned, and populations evacuated, all of which reduce the damage resulting from the storm. Improved forecasting of major winter storms allows road maintenance crews to pre-treat to reduce the disruption from snow and ice. Earthquake

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[41] Apel, H., G.T. Aronica, H. Kreibich, and A.H. Thieken. 2009. "Flood Risk Analyses—How Detailed Do We Need to Be?" *Natural Hazards* 49:79–98. https://doi.org/10.1007/s11069-008-9277-8.

[42] SPUR (San Francisco Planning and Urban Research Association). 2010. "Transportation and Rebuilding." *The Urbanist* 494. https://www.spur.org/publications/urbanist-article/2010-07-06/transportation-and-rebuilding.

forecasting, by contrast, is much more limited. Earthquake "shaking" alert systems can only provide seconds of warning. The lack of advance warning for a specific place and time is a norm that feeds into resilience analysis and planning for earthquakes.[43]

Seasonality

Seasonality occurs when the frequency of natural hazard events varies throughout the year in a regular and predictable pattern. Atlantic hurricanes (June–November), Arizona monsoons (June–September), and severe winter weather all exhibit seasonality. Seasonality can be important for resilience planning and should be included in hazard characterization. However, especially with climate change, seasonality may produce a false sense of security. Climate change can produce what is known a bit irreverently as "weather weirding." A summer-like day in February may be fun, but a heavy rain—when normally the precipitation falling on frozen ground is snow—may lead to disaster. For severe thunderstorms producing tornadoes, trends indicate that their occurrence is becoming more volatile, and the "high season" is shifting to earlier in the year. The Atlantic hurricane season is not absolute either. Named storms regularly occur outside of the season. Since 2015, there has been at least one out-of-season named storm every year, occurring in the months of January (one), April (one), and May (six).[44]

Understanding the Psychology of Uncertainty

To the extent that uncertainty varies among hazards, and depending on the degree of risk aversion, this variation may affect how people perceive the significance of a particular type of hazard. If two types of disasters have the same mean risk, but one has a larger variance in the extent of damage, people are likely to assess the disaster with the larger variance to be more significant.

MULTIPLE AND CASCADING EVENTS

Most regions in the United States are prone to multiple natural hazards. Comprehensive approaches to resilience analysis and planning must not

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[43] USGS. 2021. "ShakeAlert Earthquake Early Warning Delivery for the Pacific Northwest." https://www.usgs.gov/news/shakealert-pacific-northwest-rollout?.

[44] USGCRP. 2017. "Chapter 9: Extreme Storms" in *Climate Science Special Report: Fourth National Climate Assessment*. https://science2017.globalchange.gov/chapter/9; Wikipedia. n.d. "List of Off Season Atlantic Hurricanes." https://en.wikipedia.org/wiki/List_of_off-season_Atlantic_hurricanes.

only characterize all relevant hazard events but also analyze the potential for events to occur simultaneously or in quick succession.

Multiple-hazard analysis evaluates the effects of two or more separate hazard events, as opposed to looking at the multiple effects of a single event. (A tsunami that generates loading on a bridge from both moving water and debris is an example of multiple effects from a single event.) Multiple hazards may be concurrent or in overlapping sequence, such that the asset has not recovered from the first event before the second event occurs. The multiple hazards may be the same type of event, such as the main shock and the aftershocks of earthquakes or two successive hurricanes.[45] Multiple-hazard analysis also includes the same effects from different types of events. For example, storm surge from high winds combined with heavy rain farther up the river valley can increase the size of the area inundated with flood water.

Potentially more dangerous are multiple hazard events where the hazards interact. One hazard may compound the effect of another. A heat wave is likely to be more intense during a drought. Sea level rise may mean that port facilities designed for short-term flooding may no longer be adequate for both periodic flooding and the loading associated with long-term rise.

Cascading events occur when one hazard event triggers another, like a series of toppling dominoes. Wildfire destabilizes vegetation, so even moderate rainfall after wildfire can lead to landslides, heightened floods, and debris flow. Similarly, major hurricanes that damage vegetation can also lead to landslides and increased flooding after subsequent storms. Climate change is increasing the likelihood of cascading events.[46]

MEASURING AND MODELING HAZARD SCENARIOS

A commonly used technique for hazard characterization is to designate and describe a hazard scenario or a range of hazard scenarios. A magnitude 7 earthquake with a specified epicenter location is an example of a hazard scenario. Several different methods are available to integrate the hazard scenarios into resilience analysis.

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[45] ASCE (American Society of Civil Engineers). 2019. *Resilience-Based Performance: Next Generation Guidelines for Buildings and Lifeline Standards*. https://ascelibrary.org/doi/book/10.1061/9780784415276.

[46] Vahedifard, F., and A. AghaKouchak. 2018. "The Risk of 'Cascading' Natural Disasters Is on the Rise." *The Conversation*, October 22. https://theconversation.com/the-risk-of-cascading-natural-disasters-is-on-the-rise-104192.

Deterministic and Probabilistic Methods

The deterministic approach chooses a set of hazard scenarios that could affect the transportation asset or system. Using methods specific to the type of hazard, the approach generates the loadings from each scenario and chooses the one that presents the worst case. The loadings in the worst-case event scenario then become the controlling event for the next steps of the resilience analysis.

The probabilistic approach was developed because, in practice, the worst-case loading can be difficult to identify. The probabilistic approach uses all possible events, assigning the loadings associated with each event a weight based on its frequency of occurrence.[47] The result is a range of loading values with a probability assigned to each value. Techniques also allow the inclusion of uncertainties related to randomness and lack of information. The insurance industry uses the probabilistic approach.

Scenario-Based, Event-Based, or Time-Based Approaches

Scenario-based, event-based, and time-based approaches are methods to integrate assessments of damage, disruption, and recovery into resilience analysis.

Scenario-based hazard characterization uses one event or a small set of historical or hypothetical events to model the spatial distribution of loading intensity, such as where and how the natural hazard will interact with the natural landscape and built environment of the region of interest. Scenario-based approaches are often used to develop disaster mitigation and recovery plans.[48]

The event-based strategy, which is used in building codes and standards, including for infrastructure,[49] uses maps to designate areas that experience the same likelihood of a hazard event (e.g., events that have a 10% or greater probability over 50 years). FEMA's flood hazard maps are event-based. This strategy can identify areas that are exposed to the specified hazard event, but it is less useful for analyzing the effects of a specific hazard event. An actual hazard event will not have a spatial distribution of loadings that affects all areas equally. Techniques to address

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[47] Bommer, J.J. 2002. "Deterministic vs. Probabilistic Seismic Hazard Assessment: An Exaggerated and Obstructive Dichotomy." *Journal of Earthquake Engineering* 6(Spec 01):43–73.

[48] Jones, L.M., R.L. Bernknopf, D.A. Cox, J. Goltz, K.W. Hudnut, D.S. Mileti, S. Perry, et al. 2008. "The ShakeOut Scenario: Effects of a Potential M7.8 Earthquake on the San Andreas Fault in Southern California." U.S. Geological Survey. https://pubs.usgs.gov/of/2008/1150.

[49] See, for example, ASCE. 2017. "Minimum Design Loads and Associated Criteria for Buildings and Other Structures." ASCE/SEI 7-16.

this shortcoming involve generating a set of realistic loading scenarios that correspond to approximately the same hazard level.[50,51]

The time-based approach requires generating the spatial distribution of loading intensity for all events that could impact the region of interest over a specific time horizon. The time-based approach, which is also used by the insurance industry, is the most complex, and its application in transportation is currently limited to research. However, because the approach can produce life-cycle impact assessments over a pre-defined time horizon (e.g., over 50 years), the approach could be used to evaluate the probability of exceeding a specified level of functional loss over the design life of an infrastructure asset. The annualized impact is then computed by weighting the damage and disruption from each event based on its rate of occurrence.[52]

DATA FOR MODELS AND PROJECTIONS

Complete and accurate data and up-to-date models of natural hazards that integrate climate change are critical to characterizing hazards for resilience analysis. Transportation agencies depend on federal sources of data for meteorological, geological, and climate change–related hazards. They supplement federal data with specialized information tailored to their own unique circumstances. For example, the Colorado DOT collected data on the location and extent of burn scars and combined it with FEMA flood hazard maps to create models of likelihood and character of debris flow.[53]

The committee reviewed government sources of the data required for hazard modeling and resilience analysis; while only two important data sources are presented here for explanation, other select resources are listed in Appendix C. Drawing on the interviews and their own experiences, committee members raised specific concerns about the need to update federal information on precipitation and flood hazards.

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[50] Jayaram, N., and J. Baker. 2010. "Considering Spatial Correlation in Mixed-Effects Regression and the Impact on Ground-Motion Models." *Bulletin of The Seismological Society of America* 100:3295–3303. https://doi.org/10.1785/0120090366.

[51] Bocchini, P., V. Christou, and M.J. Miranda. 2016. "Correlated Maps for Regional Multi-Hazard Analysis: Ideas for a Novel Approach" in *Multi-Hazard Approaches to Civil Infrastructure Engineering* (P. Gardoni and J. LaFave, eds.). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-29713-2_2.

[52] Tomar, A., and H.V. Burton. 2021. "Risk-Based Assessment of the Post-Earthquake Functional Disruption and Restoration of Distributed Infrastructure Systems." *International Journal of Disaster Risk Reduction* 52:102002.

[53] Kemp, L. 2020. "Transportation Resilience Metrics." Presentation to the Committee on Transportation Resilience Metrics, September 14.

FEMA Flood Maps

FEMA produces maps of flood hazards to serve the National Flood Insurance Program (NFIP) and the associated regulatory requirements for county-level flood zone management. Historically, FEMA has targeted its investments in mapping flood hazards at populated areas or nearby areas likely to be developed. As a result, only one-third of the nation's miles of rivers and streams are mapped. An estimated 2.3 million miles of rivers and streams and 50,000 miles of coastal land remain unmapped (see Figure 2-5). As of 2019, more than 6,500 counties and communities have no FEMA flood maps and for 3,300 communities, the FEMA flood maps are more than 15 years old. Most of the unmapped areas are rural, meaning that transportation networks that cross these areas may suffer from a lack of information about flood hazards. The Biggert-Waters Flood Insurance Reform Act of 2012 set modern conditions for flood hazard mapping, including incorporating climate change. However, FEMA has struggled to keep pace with mapping needs. The Association of State Floodplain Managers has estimated that an additional infusion of \$3.2–\$11.8 billion is needed to complete the flood hazard mapping program.[54]

In addition, the flood hazard mapping methods that FEMA pioneered in the early decades of its flood programs are now more widely available. The private sector is capable of creating its own flood hazard maps, adapted to specific needs. However, there can be substantial differences in the outcomes of different hazard modeling processes. Figure 2-6 illustrates the differences between FEMA's official maps of flood hazard and flood hazard analysis produced by the models of the First Street Foundation, a nonprofit dedicated to "accurate, property-level, publicly available flood risk information."[55] One significant difference between the processes used by the private sector and those used by FEMA is that the private sector typically uses proprietary models. FEMA maps are limited in that they are probabilistic, using historical data only, and therefore do not incorporate the effects of climate change. FEMA is also required to map hazards using a public process, and its hazard determinations can be appealed.[56]

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[54] Association of State Floodplain Managers. 2020. *Flood Mapping for the Nation: A Cost Analysis for Completing and Maintaining the Nation's NFIP Flood Map Inventory.* https://asfpm-library.s3-us-west-2.amazonaws.com/FSC/MapNation/ASFPM_MaptheNation_Report_2020.pdf.

[55] First Street Foundations. n.d. "First Street Foundations Mission." https://firststreet.org/mission.

[56] Eby, M., and C. Ensor. 2019. "Understanding FEMA Flood Maps and Limitations." https://firststreet.org/flood-lab/published-research/understanding-fema-flood-maps-and-limitations.

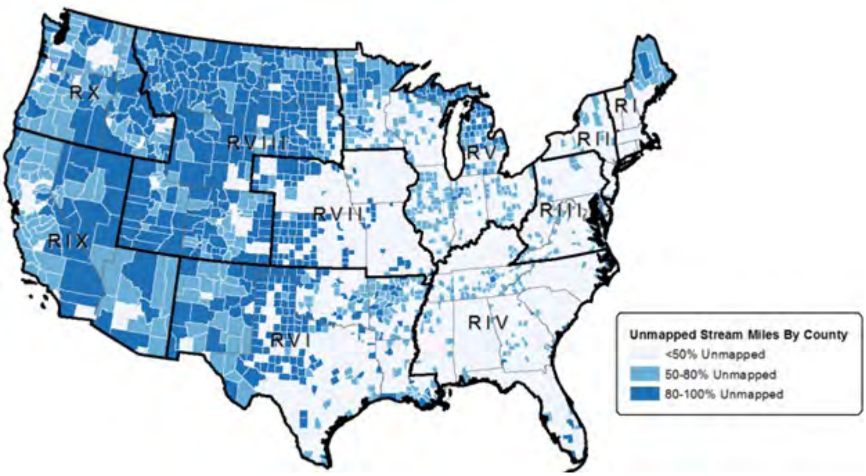

FIGURE 2-5 Unmapped stream miles by county, as of fiscal year 2019.[57]

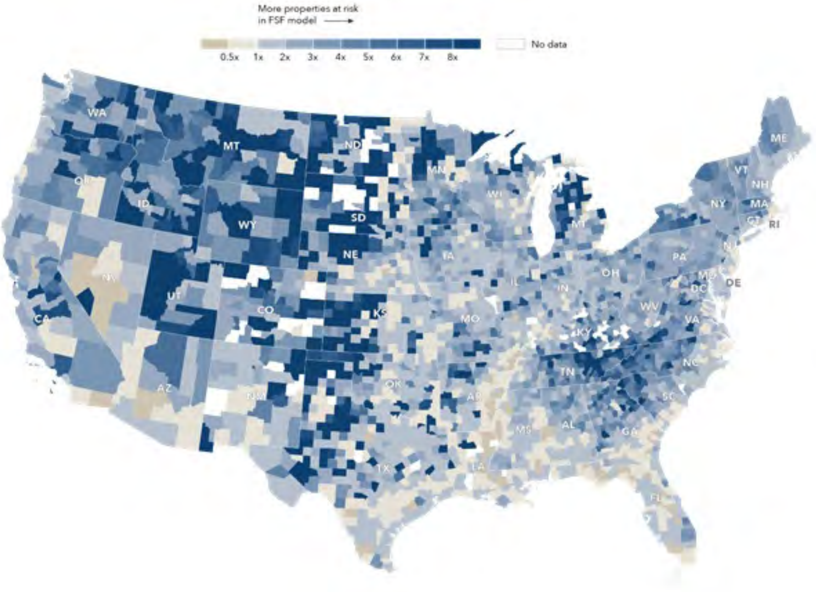

FIGURE 2-6 Difference in number of properties at substantial flood risk compared to FEMA's data.[58]

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[57] Association of State Floodplain Managers. 2020. *Flood Mapping for the Nation: A Cost Analysis for Completing and Maintaining the Nation's NFIP Flood Map Inventory.* https://asfpm-library.s3-us-west-2.amazonaws.com/FSC/MapNation/ASFPM_MaptheNation_Report_2020.pdf.

[58] Eby, M., and C. Ensor. 2019. "Understanding FEMA Flood Maps and Limitations." https://firststreet.org/flood-lab/published-research/understanding-fema-flood-maps-and-limitations.

Atlas 14

Atlas 14 is the most recent edition of a database produced by NOAA's Hydrometeorological Design Studies Center that provides detailed precipitation frequency data for most regions of the United States. Although Atlas 14 is used at the federal, state, and local levels for planning activities, engineering design, modeling of flood risks, and managing floodplain development for NFIP, its data are out of date. Importantly, the methodology used for Atlas 14 does not incorporate climate change projections. The first regional volume of Atlas 14, for the semiarid southwest, was released in 2004. Although volumes for the northeastern states and Texas were first released in 2015 and 2018, respectively, the volumes for most of the regions are more than 8–10 years old and in need of updating. The northwestern states are not covered by Atlas 14, and no funding is available to complete their volume.[59]

The weaknesses of Atlas 14 have consequences for transportation agencies. Recent studies conducted for the Virginia Transportation Research Council indicate that Virginia's rainfall index has increased, representing a significant and ongoing change from the precipitation frequencies documented by Atlas 14 for the Ohio Valley and surrounding states, last completed in 2004 and revised in 2006. More recent trends and simulated future conditions show the inadequacy of Atlas 14. The City of Virginia Beach, following analysis that extreme rainfall events will be occurring more frequently in the coming decades, recently revised its design standards manual to increase all of the volumes of design storms by 20%.[60]

Because precipitation frequency data are critical to Virginia's ability to adapt and protect coastal and riverine regions of the state from the impacts of climate change, the Commonwealth is currently collaborating with Delaware, Maryland, North Carolina, and NOAA's National Weather Center on

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[59] HDSC (Hydrometeorological Design Studies Center). n.d. "Precipitation Frequency Data Server." https://hdsc.nws.noaa.gov/hdsc/pfds/index.html; HDSC. 2019. "Progress Report for Period October 2018 to March 2019." https://www.weather.gov/media/owp/oh/hdsc/docs/201904_HDSC_PR.pdf.

[60] Morsy, M.M., Y. Shen, J.M. Sadler, A.B. Chen, F.T. Zahura, and J.L. Goodall. 2019. "Incorporating Potential Climate Change Impacts in Bridge and Culvert Design." FHWA/VTRC 20-R13. http://www.virginiadot.org/vtrc/main/online_reports/pdf/20-r13.pdf; City of Virginia Beach, Virginia. 2017. "Joint Occurrence and Probabilities of Tides and Rainfall." CIP 7-030, PWCN-15-0014, Work Orders 2 and 5A, Final Report. https://www.vbgov.com/government/departments/public-works/comp-sea-level-rise/Documents/joint-occ-prob-of-tides-rainfall-4-24-18.pdf; Smirnov, D., J. Giovannettone, S. Lawler, M. Sreetharan, J. Plummer, and B. Workman. 2018. "Analysis of Historical and Future Heavy Precipitation: City of Virginia Beach, Virginia." CIP 7-030, PWCN-15-0014, Work Order 9A. https://www.hrpdcva.gov/uploads/docs/5A_Attachment_AnalysisofHistoricalandFutureHeavyPrecipitation_Finalrev_20180326.pdf; City of Virginia Beach, Department of Public Works. 2020. *Design Standards Manual.* https://www.vbgov.com/government/departments/public-works/standards-specs/pages/default.aspx.

a four-state effort to update Atlas 14's precipitation estimates. Updated data are essential to support accurate estimates for what communities can expect from storm events; for Commonwealth agencies to have accurate forecasting projections to prepare for future rain, storm, and other climatic events; and to ensure accurate regulatory processes. Although paid for through a Federal Highway Administration pooled funding process, the updated data will be available for download from NOAA's Precipitation Frequency Data Server. A similar project is under way to update precipitation frequency data for the State of Louisiana.[61]

CHAPTER SUMMARY

Ensuring the resilience of transportation systems requires preventing natural hazards from creating the damage and disruption that leads to disastrous outcomes. Resilience analysis starts with methods to determine hazard likelihood and characteristics and must address the uncertainty about where, when, and how a hazard event is likely to occur. Comprehensive approaches to resilience analysis cover multiple hazards, including their interactions. When transportation agencies conduct resilience analysis, they need to account for regional and location-specific variations in exposure to different types of natural hazards.

The changes associated with climate change make resilience investments more pressing while also increasing the importance of integrating uncertainty into resilience analysis. In the face of this uncertainty, scenario-based approaches can be effective strategies for analyzing changing natural hazards because they consider a range of possible threats, rather than relying on point estimates. However, scenario-based analysis approaches are still affected by data and modeling quality. Transportation agencies depend on the federal government and others for up-to-date data on hazards and their effects and for modeling climate change. Currently, outdated and deficient precipitation data are a major risk for accurate damage estimates, and, similarly, incomplete and out-of-date FEMA flood maps hinder the ability to assess and prepare for major impacts from floods. The extent to which these data and modeling capabilities are lacking will affect the ability of transportation agencies to engage resilience analysis with confidence.

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[61] Commonwealth of Virginia, Office of the Governor. 2020. "Virginia Coastal Resilience Master Planning Framework, Principles and Strategies for Coastal Flood Protection and Adaptation." https://www.naturalresources.virginia.gov/initiatives/resilience--coastal-adaptation; Transportation Pooled Fund Program. 2020. "Update Precipitation Frequency Estimates for Delaware, Maryland, North Carolina and Virginia (NOAA Atlas 14 Volume 13)." Solicitation 1534. https://www.pooledfund.org/Details/Solicitation/1534; Transportation Pooled Fund Program. 2020. "Update Precipitation Frequency Estimates for Louisiana (NOAA Atlas 14 Volume 14)." Solicitation 1543. https://www.pooledfund.org/Details/Solicitation/1543.

3

Current Practice in Measuring and Managing Transportation System Resilience

Transportation agencies across the modes have taken different steps to integrate resilience analysis into their decision-making processes. Some agencies have developed comprehensive quantitative analysis procedures to estimate both the current level of resilience and the relative benefits and costs of candidate investments to improve resilience. Some have developed indicators that allow them to track progress in improving the level of transportation system resilience over time. Others have factored resilience benefits into infrastructure design guidance that can be consulted to choose designs that are most cost-effective for improving resilience. The methods used for these assessments often involve a mix of qualitative and quantitative data and reliance on expert judgment to fill data gaps.

This chapter begins with an introduction to the analytical procedures that agencies are using in the field to deliberately increase resilience, including the data used as inputs to the procedures and the intermediate measures and output metrics the procedures generate. To illustrate how these procedures work, the chapter then provides short case studies of the use of quantitative risk assessment models and tools, vulnerability assessments, resilience indicators, and design guides. The chapter concludes with a summary of the various types of metrics used in these practices.

INTRODUCTION TO CURRENT PRACTICE

An agency's resilience practices are often shaped by the context in which the practices were originally developed. For many agencies, a catalyzing event raised awareness of the risks of natural hazards. Others developed resilience practices in response to federal or state legislation.[1] Sometimes multiple factors occurring at the same time or in succession had influence. Hurricane Katrina (2005) followed by Superstorm Sandy (2012) spurred New York's Metropolitan Transportation Authority to treat resilience more explicitly. State legislation passed in 2015 required California's Port of Long Beach to develop its *Climate Adaptation and Coastal Resiliency Plan* as part of a statewide Integrated Climate Adaptation and Resiliency Program.[2] Hurricane Isabel (2003) prompted early attention within the Hampton Roads Transportation Planning Organization (HRTPO), while the organization's growing interest in advanced modeling techniques was motivated by the 2015 Fixing America's Surface Transportation (FAST) Act's requirement to incorporate resilience considerations into state and metropolitan long-range planning. The Colorado Department of Transportation's (DOT's) resilience efforts can be traced to several influences, including major flooding in 2013, state legislation on emergency response enacted in 2018, and the federal regulations that limit emergency relief funds to highway projects that restore infrastructure only to its pre-disaster state unless the owner can show that the project reduces costs in the long run.[3]

Federal, state, and local transportation officials have put significant effort into developing and encouraging the adoption of resilience analysis over the past decade. The challenge they face, however, is prompting agencies to take a comprehensive approach to resilience analysis, rather than the practice of focusing on resilience to specific hazards and for certain types of assets only. There may be good reasons for this practice. Policy makers may appropriately emphasize only the type of natural hazard that is the most likely threat to their infrastructure. They may focus only on the types of assets that seem most vulnerable. Data availability or modeling capability may limit analysis. Finally, there may be diminishing returns to additional complexity. Absent incentives, tools, and data for comprehensive approaches to resilience, it can be rational for agencies to limit resilience analysis to the goals that policy makers assign or the types of strategies and actions that they can feasibly implement on their own.

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[1] USGCRP (U.S. Global Change Research Program). 2018. "Chapter 12" in *Fourth National Climate Assessment (NCA4)*. https://nca2018.globalchange.gov/chapter/12.

[2] Port of Long Beach. 2016. "Climate Adaptation and Coastal Resiliency Plan." https://www.slc.ca.gov/wp-content/uploads/2018/10/POLB.pdf; State of California. n.d. "Integrated Climate Adaptation and Resiliency Program." https://opr.ca.gov/planning/icarp.

[3] House Bill 18-1394, Colorado State Legislature, May 24, 2018, https://leg.colorado.gov/sites/default/files/2018a_1394_signed.pdf; Colorado DOT (Department of Transportation). 2020. "Risk and Resilience Analysis Procedure," pp. 1–2. https://www.codot.gov/programs/planning/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf.

TYPES OF METRICS USED IN PRACTICE

While a single, direct measure of resilience cannot be readily developed or commonly applied, there are common elements in the methods that agencies use to evaluate their resilience to natural hazards and the likely effectiveness of strategies and actions to improve resilience. These elements include analysis methods and metrics for (1) the likelihood (or probability) of natural hazard events (sometimes called "exposure"); (2) the vulnerability (sometimes called "sensitivity") of the infrastructure or transportation system to damage or disruption; (3) the consequences of a particular level of damage or disruption, which are often expressed as a combination of owner costs and user costs; and (4) the criticality, or importance, of the infrastructure or system, which may include usage and other measures that reflect the importance of an asset, node, network, or system in broader economic and social terms.

Discussions of procedures for measuring the level of resilience and the net benefits of investments in improving resilience can be confusing because different practitioners use different terms for the same concepts. Some resilience assessment approaches refer to the likelihood of a particular kind of natural hazard as the "threat" or "threat probability," while others use the term "exposure" to mean the same thing. The Federal Highway Administration's (FHWA's) Vulnerability Assessment Scoring Tool (VAST) uses the word "sensitivity" to refer to the likely physical damage or disruption to an infrastructure asset due to a hazard event, while Risk Analysis and Management for Critical Asset Protection (RAMCAP) models generally use the term "vulnerability" to refer to the likelihood of damage. In the VAST context, vulnerability is a function of the asset's or system's sensitivity to hazards or climate effects, exposure to extreme weather and climate effects, and the system's adaptive capacity. RAMCAP uses the word "risk" to mean the product of the hazard likelihood, the asset "vulnerability," and the monetary consequences resulting from the hazard affecting the asset; FHWA refers to "risk" as the product of the hazard likelihood and the consequences. Hence, the VAST and the RAMCAP models both use the term "vulnerability," but they use it to mean two different things. A shared taxonomy of terms is desperately needed.

Hazard Likelihood and Character

Analysis methods that describe the character and likelihood of natural hazard events are covered in more detail in Chapter 2. Most analytic procedures for assessing resilience start with an assessment of what natural hazards can be expected in a particular geographic area and what the likelihood is of a given hazard event of a given magnitude (e.g., a Category 3 hurricane).

Vulnerability

Vulnerability evaluates the effects of a specific natural hazard of a particular magnitude on an infrastructure asset or transportation service. Thus, measures of vulnerability assess susceptibility of infrastructure assets to damage by particular hazard events. Assessments of vulnerability take into account where the asset is located, its design, and its condition. Vulnerability can be reduced by investments that increase the robustness of the asset and mitigate the damaging effects of natural hazards, and sometimes by relocating the asset. Vulnerability assessments are used to identify at-risk assets and to prioritize which assets may require additional analysis for risk or mitigation.

Consequences

Consequences are measures of the direct and (if possible) indirect impacts of the damage or disruption to the transportation asset, node, network, or system. Consequences are often split between the owner and the users. For example, consequences for the owner may include costs to repair damage and restore service, while consequences to the users would include costs of detours, delays, and missed trips. Consequences would also include death and injury of personnel or travelers. Consequences may be dependent on the level of redundancy in the transportation system—to the extent that travelers and freight carriers have feasible alternative routes to circumvent damaged infrastructure, the consequences of infrastructure damage are reduced. Indirect consequences can include effects on communities and businesses due to a reduction in accessibility and mobility, failed deliveries, or disruptions of economic and social activities.

Risk

Risk is the overall likelihood of loss due to natural hazards during a particular time period (typically 1 year), taking into account the likelihood of a hazard event; the vulnerability of the infrastructure; and the economic and social consequences of the damage to the infrastructure for asset owners, asset users, and communities. Representing expected loss due to natural hazards, risk is a key output measure of the resilience analysis and an indicator of the level of resilience that is directly useful after analyzing how it changes in response to investments in reduced vulnerability.

Criticality

Criticality is a measure of the importance of the *function* of the transportation asset, node, network, or system. Criticality includes some of the same elements as "consequences" (such as costs to users) but also includes broader economic and social impacts, for example, on shippers of freight movements that are disrupted and on tourism industries due to disruptions to passenger transportation. Criticality also takes into account equity effects, such as the distribution of disruption impacts across socially and economically vulnerable populations. Costs to infrastructure owners to repair damage or restore service are not normally included in criticality.

Like risk or vulnerability assessments, criticality measures are used for prioritization. The selection of the component measures for criticality is typically done on a parallel track to the rest of the resilience analysis. Because criticality measures involve broader economic and social concerns, criticality assessment typically involves stakeholder or public consultation. For its resilience-informed, long-range metropolitan transportation planning process, HRTPO defines criticality as "regional significance" and includes among its many component measures usage and travel time as well as access to major employment centers, tourism destinations, and low-income communities.[4]

Prioritization based on criticality can be done at different stages of the resilience analysis and resilience-informed decision making. FHWA recommends that criticality prioritization occur early in the assessment process to target subsequent vulnerability analysis and resilience interventions to the more important transportation elements.[5]

There is an emerging practice of defining resilience to be the intersection of vulnerability and criticality or of risk and criticality. One way to present this result is through a matrix, as in Figure 3-1. In this approach, both vulnerability and criticality together guide priority setting. As an example, elements evaluated for resilience investment would progressively increase in priority from those with low criticality/low vulnerability (lower left corner cell, in dark green) to those with high criticality/high vulnerability (upper right corner cell, in red).

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[4] Stith, D.M. 2020. "Integrating Resilience into Planning." Hampton Roads Transportation Planning Organization, October 7. https://www.hrtpo.org/uploads/docs/P9-HRTPO-IntegratingResilience-LRTP-10.07.20.pdf.

[5] FHWA (Federal Highway Administration). 2014. "Assessing Criticality in the Transportation Adaptation Planning." https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/criticality_guidance.

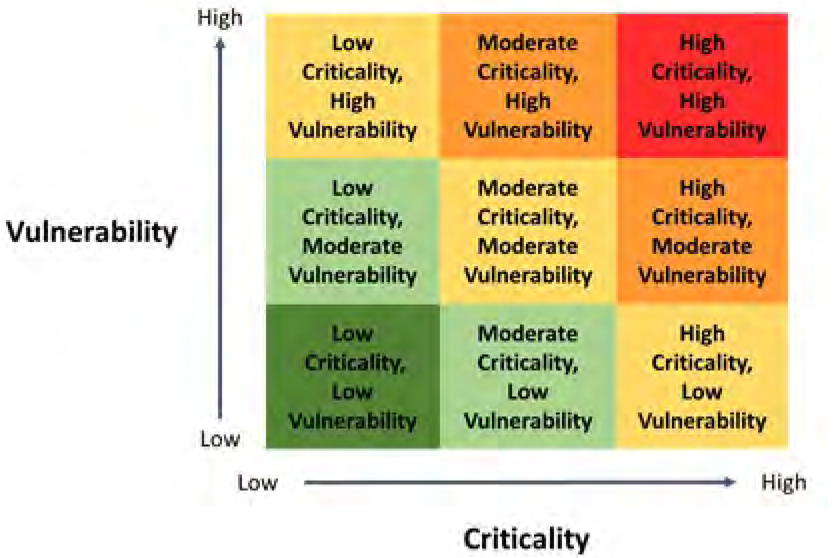

FIGURE 3-1 Resilience can be assessed by a matrix of criticality and vulnerability.[6]

Input Data and Derived Measures

The resilience analysis process requires input data, such as hazards, asset conditions, and functionality. These are used in the agency's analytical process to measure (or estimate) vulnerability, criticality, and consequences to guide the selection of resilience improvements. These analytic measures may also be used to estimate overall risk or resilience. Outputs of resilience analysis processes may be quantitative data and measures, qualitative indicators (though often based on quantitative input data), or qualitative descriptions.

The case studies that follow show how agencies use a variety of input data, quantitative and qualitative measures, indicators, and descriptors to assess asset or system resilience.

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[6] Adapted from the Houston-Galveston Area Council. 2021. "Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program Report." https://www.h-gac.com/getmedia/4a9d1f74-a43c-4279-8f82-f11da502e1e8/H-GAC-Resiliency-Pilot-Program-Final-Report.pdf.

FIGURE 3-2 Location of the FHWA pilots.[7]
NOTE: MPO = Metropolitan Planning Organization.

FEDERAL PILOT PROGRAMS

Pilot projects funded by the U.S. Department of Transportation (U.S. DOT) through FHWA, the Federal Transit Administration (FTA), the Federal Aviation Administration (FAA), and the Office of the Secretary have been a significant means of advancing the practice of resilience planning and decision making among transportation agencies.

FHWA has conducted five series of resilience pilots since 2010, for a total of 46 pilots across the United States (see Figure 3-2).[8] Series subjects included asset management and vulnerability assessments. Each pilot series had a well-defined set of goals and tested resilience concepts or guidelines developed or promoted by FHWA. Each pilot series provided the resources necessary to launch resilience practices in transportation and planning organizations across the country, while providing FHWA with the lessons

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[7] FHWA. 2020. "Resilience Pilots." https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/index.cfm?format=list#map.

[8] FHWA. 2020. "Resilience Pilots." https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/index.cfm?format=list#map.

learned to further develop or update its guidance documents and resilience tools.

FTA conducted pilots through its Climate Change Adaptation Initiative, launched in 2011.[9] The program funded pilots for nine transit agencies in seven locations.[10] Each pilot identified current and future climate hazards (in particular flooding and extreme precipitation, extreme heat, sea level rise, and tropical storms and hurricanes), assessed system vulnerabilities, and developed adaptation strategies for the specific transit system. Individual pilots tested developing resilience indicators, using life-cycle cost assessment to evaluate adaptation actions, and incorporating vulnerabilities into an asset management system.

COMPREHENSIVE APPROACHES TO RESILIENCE

Although many agencies mix quantitative and qualitative methods in their resilience assessments, some agencies are experimenting with comprehensive approaches to resilience that emphasize quantitative analyses of risk and resilience. As part of their multi-hazard, system-wide assessment of resilience, the Colorado DOT and the Utah DOT have used the RAMCAP model to produce quantitative estimates of the reduction in risk associated with proposed investments in improving the resilience of their highway assets. Hazus-MH and the Resilience and Disaster Recovery Metamodel, still under development, are examples of tools designed to quantify the risk from hazard events and the costs and benefits of investments in resilience.

RAMCAP Models

The most comprehensive resilience assessment procedures currently in use are based on the RAMCAP model developed by the ASME (formerly known as the American Society of Mechanical Engineers) Innovative Technologies Institute, LLC, to provide a consistent way to evaluate risk across different types of assets and hazards (see Box 3-1).

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[9] FTA (Federal Transit Administration). n.d. "Transit and Climate Change Adaptation: Synthesis of FTA-Funded Pilot Projects." https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA0069_Research_Report_Summary.pdf.

[10] FTA. 2014. "Transit and Climate Change Adaptation: Synthesis of FTA-Funded Pilot Projects." Report No. 0069. https://cms7.fta.dot.gov/sites/fta.dot.gov/files/FTA_Report_No._0069.pdf.

BOX 3-1
RAMCAP Plus[a]—Basic Model Structure

The RAMCAP model grew out of a 2002 White House conference on the protection of critical infrastructure. The highest priority of the more than 100 senior executives from the private sector in attendance was the creation of "an objective, consistent and efficient method for assessing and reducing infrastructure risks in terms directly comparable among the assets of a given sector and across sectors."[a]

RAMCAP Plus is the most current version of the continuing development of RAMCAP. The RAMCAP Plus Process for analysis is divided into seven steps:

Step 1 – Asset Characterization
Step 2 – Threat Characterization
Step 3 – Consequence Analysis
Step 4 – Vulnerability Analysis
Step 5 – Threat Assessment
Step 6 – Risk and Resilience Assessment
Step 7 – Risk and Resilience Management

RAMCAP calculates risk based on the "worst reasonable consequence" resulting from damage of critical infrastructure assets. RAMCAP also requires developing a threat (or hazard) scenario that characterizes the threat, including its magnitude. Risk is computed as follows:

Risk = Threat Probability × Vulnerability × Consequence

Threat (or hazard) probability is the likelihood that a given asset will experience the threat scenario. Vulnerability is the probability that an asset will be damaged or destroyed in the given threat scenario. Consequence is the cost to asset owners and users resulting from the disaster scenario. RAMCAP does not include a measure of criticality, per se, but it does take into account broader economic impacts of service disruptions that are typically taken into account in criticality estimates.

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[a] ASME Innovative Technologies Institute, LLC. 2009. *All Hazards Risk and Resilience: Prioritizing Critical Infrastructures Using the RAMCAP Plus Approach*. https://files.asme.org/ASMEITI/RAMCAP/17978.pdf.

Colorado DOT

RAMCAP offers a systematic and quantitative framework for integrating risk and resilience, and Colorado DOT's application has particular value in that it moves the core ideas of RAMCAP into practice. Colorado DOT's "Risk and Resilience Analysis Procedure" is designed to bring natural hazards into its risk-based asset management program. It covers rockfalls, floods, and debris flows after fire for roadways, bridges, and culverts. The resilience analysis produces two output measures—annual risk and level of resilience. Risk is measured in terms of the expected costs to the asset's owners and users from each natural hazard. Level of resilience measures the overall level of resilience for specific highway segments, taking into account both the cumulative annual risk and a broader range of criticality measures indicating the importance of the asset to society.[11]

Colorado DOT's procedure uses consistent criteria and methods to screen for risk and criticality and to conduct benefit-cost analysis (BCA) for a defined set of potential mitigation measures. The Colorado DOT is working to automate more of the data-entry process, which has been conducted manually for specific projects, so that it can be done in batches by type of natural hazard or asset. Aggregate measures of annual risk can also be produced across natural hazard types.

Colorado DOT's approach measures annual risk in dollars. It defines risk as the product of the likelihood of the hazard, the vulnerability of the asset to the hazard, and the consequences of the damage from the hazard in terms of costs to owners and users. Both the likelihood of the hazard and the vulnerability of the asset are calculated as probabilities. Risk is measured as an expected annual cost due to all of the hazards considered. The Colorado DOT thus uses input data to estimate several intermediate measures—hazard likelihood, vulnerability, and consequences—and then uses those intermediate measures to calculate the output measure—annual risk. The Colorado DOT also uses input data to calculate another intermediate measure, criticality, which it uses to calculate the level of resilience.

To calculate the threat probability (annual likelihood of floods, rockfalls, and debris flow), the Colorado DOT uses historical data on frequency and magnitude of hazard events. The analysis produces maps that identify the likelihood of natural hazards as probabilities. The probability maps do not yet include the projected impacts of climate change or other changes in extreme weather.

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[11] This section draws on Colorado DOT. 2020. "Risk and Resilience Analysis Procedure." https://www.codot.gov/programs/planning/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf; Kemp, L. 2020. Presentation to the Committee on Transportation Resilience Metrics, September 14.

Vulnerability, the second intermediate measure for annual risk, is defined as the probability of damage to an asset caused by a specific hazard. Specifically, it is "the probability of the Worst Reasonable Case occurring," assuming that a hazard event has happened. Input data for vulnerability incorporate the physical characteristics of the asset and its location. The procedure assigns these probabilities based on guidance produced from a mix of published research, empirical data, and expert judgment.

To calculate the consequences of an event (the third intermediate measure used in calculating annual risk), the analysis must first define what is meant by an "event," including its characteristics. The Colorado DOT chose to use the Worst Reasonable Case as the event, defined as "the maximum realistic losses." The Colorado DOT defined a Worst Reasonable Case for 11 hazard/asset pairs (e.g., rockfall/roadway or flood/bridge approach) from the perspective of costs to both owners and users.

To calculate the consequences to owners of the Worst Reasonable Case event, the procedure measures the costs of asset replacement and cleanup. Staff working through a collaborative workshop process identified these costs for each hazard/asset pair.

For consequences to users, the Colorado DOT defined the Worst Reasonable Case event in terms of the "maximum number of full or partial closure days." To develop costs for users, the procedure divides users into passenger and freight traffic, developing separate models of costs per mile and per hour for each. The calculation of user costs also required the development of a new traffic model to measure the length of detours required by loss of service on a highway segment.

To calculate the benefits of mitigation actions, the effects of these actions on reducing vulnerability are assessed. Actions designed to mitigate or prevent harm result in a lower vulnerability probability. These differences in vulnerability then allow for a comparison of annual risk with and without a specified investment in mitigation to produce an estimate in dollars of the benefits of mitigation.

In addition to the calculation of annual risk, the Colorado DOT defines "criticality" as a "measure of the importance of an asset to the resilience of an overall system." The "overall system" for highways is defined as highways in Colorado on the National Highway System or otherwise owned by the Colorado DOT. To measure criticality, the procedure combines six variables. Three are highway measures: average annual daily traffic, functional classification, and system redundancy. The other three are economic and social indicators measured at the county level. Freight value and tourism dollars generated are measured in millions of dollars per year. The social indicator, the Social Vulnerability Index (SoVI®), was obtained from the University of South Carolina Hazards and Vulnerability Research Institute. SoVI® combines metrics from 29 socioeconomic indicators representing characteristics of the people in each county.[12] The criticality procedure then transforms each of the six metrics into a score from 1 to 5, which is summed with equal weighting into an overall criticality score. The criticality score is further categorized as low, medium, and high. The Colorado DOT rated 21% of its highway mileage as highly critical.

Colorado DOT's level of resilience metric is a matrix that displays annual risk against criticality scores. For each mile of the highway system, an aggregate annual risk—across all hazards and asset types—is calculated. The miles are then ranked from low to high annual risk and sorted into quintiles. The procedure then assigns a "resilience" score of A through E, from best to worst, for each cumulative annual risk/criticality pair (Figure 3-3 illustrates an example). Calculating aggregate annual risk for every mile of highway allows for overall assessments of resilience but also requires more extensive data than analysis approaches that focus on a more limited list of specific locations, hazards, and asset types.

The Colorado DOT initiated its application of the RAMCAP model by doing a pilot study of highway assets that had twice been damaged by natural disasters since 1997 and hence were likely to be at particularly high risk. The case study only considered assets that were under consideration for the Statewide Transportation Improvement Program (STIP). The selection criterion of twice damaged substituted for a more comprehensive assessment of natural hazards, limited the scope of the necessary asset inventory, and informed the baseline analysis of the impacts of natural hazards. The stipulation that these assets be part of projects proposed for the STIP served as a proxy for determining their importance. The agency then used its modeling capabilities to assess interventions, measured in terms of the owner costs of damages and the user costs of delays and detours. The results of the resilience analysis then fed into the larger project selection process for the STIP.

Utah DOT

The Utah DOT also uses RAMCAP, with some significant differences from Colorado DOT's analysis procedure. The Utah DOT selected a larger group of natural hazards for more in-depth analysis: avalanches and earthquakes (for bridges only) in addition to rockfalls, floods, and debris flows. The Utah DOT does not use "vulnerability" (the probability of damage to an asset from a hazard event) to calculate annual risk, though it intends to do so in the future. Instead, the agency treated the probability of a hazard as the probability of a hazard great enough to cause total failure of the asset. If total failure of the asset occurs, then the "vulnerability" term is

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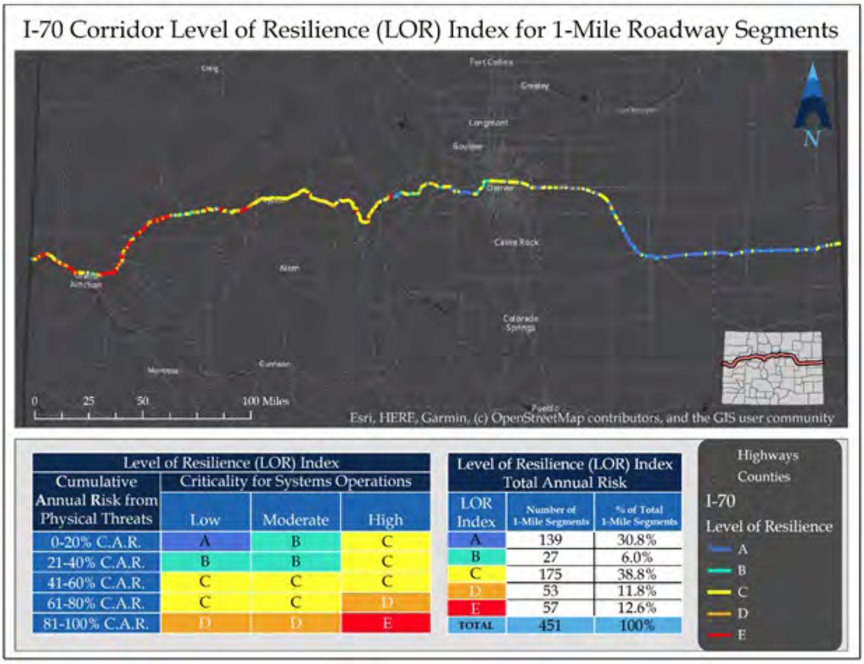
[12] Hazard and Vulnerability Research Institute. n.d. "SoVI." University of South Carolina. http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-0.


I-70 Corridor Level of Resilience (LOR) Index for 1-Mile Roadway Segments

Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Level of Resilience (LOR) Index			
Cumulative Annual Risk from Physical Threats	Criticality for Systems Operations		
	Low	Moderate	High
0-20% C.A.R.	A	B	C
21-40% C.A.R.	B	B	C
41-60% C.A.R.	C	C	C
61-80% C.A.R.	C	C	D
81-100% C.A.R.	D	D	E

Level of Resilience (LOR) Index Total Annual Risk		
LOR Index	Number of 1-Mile Segments	% of Total 1-Mile Segments
A	139	30.8%
B	27	6.0%
C	175	38.8%
D	53	11.8%
E	57	12.6%
TOTAL	451	100%

FIGURE 3-3 The Colorado DOT is experimenting with a measure of resilience that combines measures for cumulative annual risk and criticality in a way that can assess the comparative resilience of an entire highway system. This figure shows variations in the level of resilience for segments of I-70.[13]

equal to 1, and hence the term drops out of the equation when the terms are multiplied together. The Utah DOT does use the change in sensitivity (or vulnerability), defined as "a measure of how much damage will occur" from a particular event, to calculate the benefits of efforts to mitigate risk by reducing sensitivity. It calculates sensitivity for a continuous range of hazard events from no damage to complete failure. For consequences, the Utah DOT also uses owner costs and user costs but has developed its own way to measure them. The Utah DOT uses a measure of criticality to set priorities for different mitigation investments, using only highway-related factors—redundancy, average annual daily traffic, and truck traffic—and weighs redundancy to be more than twice as important as each of the other two. The Utah DOT also uses criticality and annual risk as quantitative measures

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[13] Colorado DOT. 2020. "Risk and Resilience Analysis Procedure." https://www.codot.gov/programs/planning/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf.

to produce a quantitative measure of resilience, defined as 1 divided by the product of risk and criticality. As with the Colorado DOT, the Utah DOT used pilot studies (including one focusing on I-15) to develop its resilience methodology.[14]

Hazus-MH

The most popular tool for estimating the impacts of natural hazards is Hazus-MH, a nationally standardized risk modeling methodology that is managed by the Federal Emergency Management Agency. The geographic information system–based tool identifies and maps regions exposed to earthquakes, tsunamis, hurricanes, and coastal and riverine flooding and produces quantitative estimates of the direct physical, economic, and social impacts of hazard events (see Figure 3-4). Hazus-MH uses information on buildings, infrastructure, population, extreme event extent and intensity, and damage functions to estimate losses and risks. Hazus-MH was designed for simplicity of use and comes with default databases pre-embedded in the program. Hazus-MH considers the following transportation infrastructure: highway, rail, light rail, bus, port, ferry, and airport. Its inventories of buildings are periodically updated, and users can import their own data on buildings and structures. It can also perform a rough assessment of the recovery curves described in this chapter.[15]

Hazus-MH can be used to analyze the cost-effectiveness of common mitigation strategies, such as elevating buildings and structures to prevent flood damage. It can be effective for identifying risks and helping support decisions for major investments on a class of assets in a region. However, because its analysis resolution is coarse, Hazus-MH may not be appropriate for many types of transportation impacts and for smaller mitigation actions.[16]

Resilience and Disaster Recovery Metamodel

Being developed to fill the risk analysis gaps left by tools such as Hazus-MH, the Resilience and Disaster Recovery Metamodel (RDRM) is part of a pilot project sponsored by FHWA with U.S. DOT's Office of the Assistant Secretary for Research and Technology and Office of Intelligence, Security, and Emergency Response; HRTPO; and the John A. Volpe National

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[14] Utah DOT. 2020. "UDOT Asset Risk Management Process."

[15] FEMA (Federal Emergency Management Agency)–U.S. Department of Homeland Security. 2019. "Hazus 4.2."

[16] FEMA. 2020. "What Is Hazus?" https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/about.

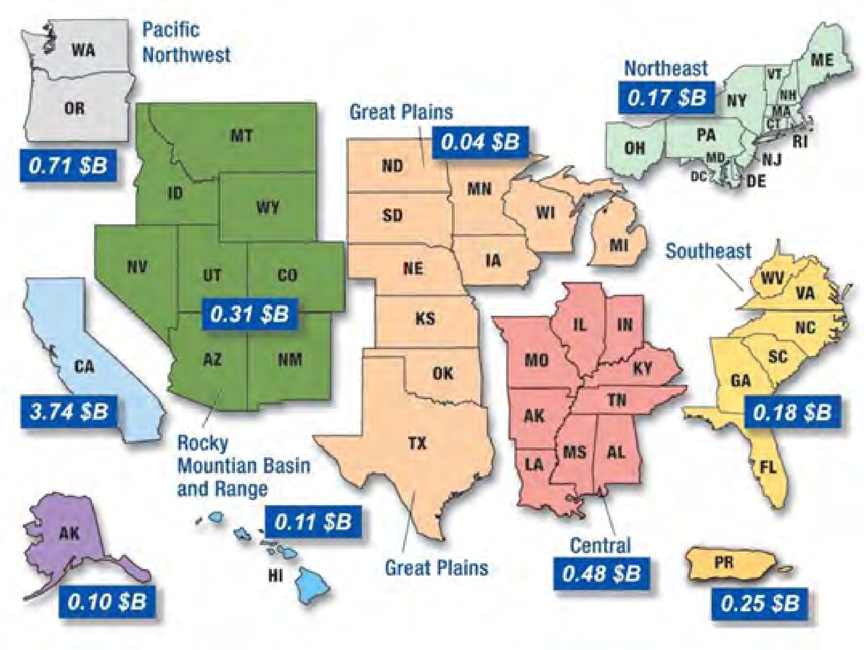

FIGURE 3-4 Hazus-MH can be used to compare regional seismic risk by annualized earthquake losses.[17]

Transportation Systems Center.[18] The FAST Act required the incorporation of resilience considerations into transportation planning, and the development of the RDRM is part of FHWA's effort to respond to that mandate. The goal of the RDRM project is to develop a "nationally replicable modeling tool that quantifies direct and indirect costs" of the kinds of disruptive events associated with natural hazards. It will allow calculation of benefits and costs and returns on investment of various resilience investments.

The power of the tool is that it will allow transportation agencies to use hazard scenarios to compare the costs of different levels of disruption against the costs of potential hazard mitigation or adaptation actions. The RDRM uses many of the same kinds of input data and intermediate

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[17] Jaiswal, K., D. Bausch, J. Rozelle, J. Holub, and S. McGowan. 2017. *Hazus® Estimated Annualized Earthquake Losses for the United States.* FEMA P-366, April. https://www.fema.gov/sites/default/files/2020-07/fema_earthquakes_hazus-estimated-annualized-earthquake-losses-for-the-united-states_20170401.pdf.

[18] The information in this section draws from the presentation of D.M. Stith, Principal Transportation Planner, HRTPO, to the Committee on Transportation Resilience Metrics, September 17.

measures as RAMCAP models, such as hazard probabilities, vulnerability of infrastructure assets to particular hazards, and the consequences of damages to infrastructure. It is intended to be used in conjunction with the travel demand models used by metropolitan and regional planning organizations. It focuses particularly on the wider economic impacts of disaster-related disruptions of the transportation network, including on regional economic impacts, disruptions to port access, access for emergency vehicles, and commuting patterns. It pays particular attention to uncertainties in the input data and estimates standard deviations in the benefits and costs of different investment options. HRTPO is using the tool to develop scenarios for its long-range transportation plan and to evaluate projects for prioritization in the plan. Examples of the HRTPO regional significance prioritization measures include usage volumes/ridership; travel time reliability; impact on freight movement; defense, port, and tourism access; and access to areas with high unemployment and low-income areas.

Although HRTPO is analyzing the impacts of sea level rise, the resilience metamodel is designed to be able to address a variety of natural hazards. If the model design is successful, the resilience metamodel could become a widely used tool to measure the level of resilience and evaluate potential investments to improve resilience. It could be used, along with travel demand models, land use models, and economic models, in developing long-range transportation plans and their associated capital improvement programs.

VULNERABILITY ASSESSMENTS

Vulnerability assessments represent a first step toward developing a plan for improving resilience. They help a transportation agency or a multistakeholder planning process prioritize which specific assets, services, or systems are most at risk from natural hazards and should be included in the subsequent analysis that identifies and evaluates strategies and actions designed to increase resilience. Metrics are used in vulnerability assessments to identify the character and likelihood of natural hazard events and compare the vulnerability of different types of assets.

U.S. DOT Vulnerability Assessment Tools

To encourage and guide vulnerability assessments, U.S. DOT developed VAST in 2015. The tool provides libraries of indicators for the three facets of vulnerability: exposure (equivalent to what RAMCAP models call threat probability), sensitivity (equivalent to what RAMCAP models call vulnerability), and adaptive capacity (similar to the concept of redundancy). The indicators are in the form of scores of increasing vulnerability, on a scale of 1 to 4. For example, for sensitivity to higher temperatures, ballast type is one indicator for rail, and age of buses is one indicator for mass transit services. The libraries cover six asset types (roads, bridges, rail lines, ports, airports, and transit assets) and five climate stressors (temperature changes, precipitation changes, sea level rise, storm surge, and wind). The tool only covers climate-related hazards and not geophysical hazards, such as earthquakes. The scores are designed to allow for comparing the vulnerability of different types of assets.[19]

In addition, FHWA's *Vulnerability and Adaptation Framework* provides guidance on how to use vulnerability assessments in resilience planning processes.[20] As a result, vulnerability assessments are becoming a prevalent practice in resilience planning.

Vulnerability Assessment Case Study: The San Diego International Airport

The *Climate Resilience Plan* from the San Diego International Airport (SDIA) shows how quantitative approaches to hazard likelihood and character fit into vulnerability assessments and resilience planning.

Managers at the San Diego County Regional Airport Authority, which operates SDIA, conducted a vulnerability assessment funded through the Sustainable Management Planning grant program from FAA as part of developing a Climate Resilience Plan. The vulnerability assessment informed subsequent steps in the planning process, including evaluating consequences, setting goals and targets, and selecting a list of actions designed to increase the airport's resilience. For the vulnerability assessment, three climate stressors were examined—sea level rise, precipitation, and heat—and the airport's assets and operating systems were grouped into five analysis categories: runways, taxiways, and navigational systems; airport facilities; tenant facilities; ground transportation networks (including access roads and parking lots); and the habitat of the least tern, an endangered bird species.[21]

The vulnerability assessment follows the pattern laid out in FHWA's VAST, using the analysis process outlined in Figure 3-5, to select which assets were vulnerable to the climate stressors. Step 1 defines the exposure

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[19] U.S. DOT's "Sensitivity Matrix" covers a wider range of modes and climate stressors for the sensitivity variable in vulnerability assessments. U.S. DOT. 2015. "Vulnerability Assessment Scoring Tool." https://www.fhwa.dot.gov/environment/sustainability/resilience/tools; U.S. DOT. 2015. "Sensitivity Matrix." https://www.fhwa.dot.gov/environment/sustainability/resilience/tools.

[20] FHWA. 2017. *Vulnerability and Adaptation Framework, Third Edition.* https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework.

[21] SDIA (San Diego International Airport). 2020. Climate Resilience Plan; Reed, B. 2020. Presentation to the Committee on Transportation Resilience Metrics, September 17.

FIGURE 3-5 Steps for the vulnerability assessment conducted by the San Diego International Airport.[22]

to the hazard in terms of its nature and degree. Step 2 identifies the sensitivity or "the degree to which the physical condition and functionality of an asset, population, or system is affected by climate stressors." The analysis of adaptive capacity in Step 3 requires identifying the "inherent characteristics that allow the asset to readily respond or adapt" to the stressors. Factors that influenced sensitivity include, for example, the presence of electrical equipment, while adaptive capacity was influenced by factors such as the ability to elevate or relocate assets. Although analysis of sensitivity and adaptive capacity yielded important information, analysis of exposure turned out to be the most important of the three for assessing vulnerability.

To analyze exposure, scenarios were developed for precipitation, heat, and flooding connected to sea level rise and storm surge.[23] The scenarios cover multiple time frames, from the present to the year 2100. For these climate change impact scenarios, the SDIA analysts and planners benefited from guidance from the State of California; such guidance streamlined the resilience planning process and lessened the resources that the airport needed for its assessment. The climate change models showed no change in precipitation from the present for 2050 and only small changes in 2100. For storm surge on top of sea level rise, multiple scenarios were developed corresponding to different levels of carbon emissions, and areas projected to be exposed to flooding were mapped. The areas expected to be flooded with a probability of 5% were defined as the high projections for 2030, 2050, and 2100. For 2100, this amount is 4.9 feet of sea level rise. Figure 3-6 is the map of the high scenario for 2100; the maximum high tide is in blue and the additional flooding from storm surge is in green.

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[22] SDIA. 2020. *Climate Resilience Plan*; Reed, B. 2020. Presentation to the Committee on Transportation Resilience Metrics, September 17.

[23] They explored other natural hazards including wildfires and changes in wind from storms, but data and modeling for projections were not available to develop quantitative scenarios.

FIGURE 3-6 San Diego International Airport flooding forecast due to sea level rise, maximum high tide, and 100-year storm surge.[24]

The San Diego County Regional Airport Authority then went beyond the vulnerability assessment to examine the consequences of the vulnerabilities identified and developed a preliminary list of initiatives to mitigate those vulnerabilities. For assets deemed vulnerable, they conducted a "high-level risk assessment" that analyzed the potential economic, social, and environmental consequences of the damage or disruption associated with each climate stressor. Economic consequences were considered in terms of asset damage and service disruption. Social consequences are made up of the loss of jobs, the quality of passenger experience, and life safety. Environmental consequences focus on loss of habitat for the endangered least tern and reduction of water quality in the San Diego Bay. The analysis of the consequences consists of qualitative descriptions.

A vulnerability profile was then created for each asset category, using the results of the vulnerability assessment and the high-level risk assessment.

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[24] SDIA. 2020. *Climate Resilience Plan*; Reed, B. 2020. Presentation to the Committee on Transportation Resilience Metrics, September 17.

The vulnerability profiles identified, through qualitative descriptions, which specific assets are vulnerable to which stressor and during which time frame. The specificity in the vulnerability profiles allowed for the development of a corresponding list of initiatives to be implemented in the near, medium, and long term. The identified initiatives were built around three strategic areas: infrastructure (how we build), governance (how we manage), and awareness (how we learn).

The infrastructure initiatives vary in their specificity. One initiative targeting heat proposes to "reduce heat island effect by resurfacing dark rooftops and pavements with remaining lifespans of more than 10 years." Another initiative targeting the flooding associated with sea level rise and storm surge states the following: "raise shoreline to protect assets," either by permanent or temporary barriers. These alternatives still need to be evaluated, in coordination with the external parties, for cost effectiveness.[25]

The goal of the *Climate Resilience Plan* is to "reduce risks associated with climate change."[26] The initial targets focus on achieving "zero reports of negative impacts on Airport facilities due to flooding or extreme heat days" by the year 2035,[27] but the San Diego County Regional Airport Authority also cites forecasts of climate change out to the year 2100, targeting the airport to be resilient to a flood that has no more than a 5% chance of occurring in the year 2100.

RESILIENCE INDICATORS: LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

Resilience indicators track characteristics that suggest whether an asset or a system is resilient. Although agencies sometimes resort to using indicators in cases where producing the quantitative metric itself is difficult, indicators can also be used to provide useful guidance for management decision making.

The Los Angeles County Metropolitan Transportation Authority (LACMTA) uses indicators to evaluate its progress in implementing a program designed to increase resilience. As appropriate for an agency that both operates transportation services and constructs and maintains transportation infrastructure, LACMTA's resilience indicators cover a broad range of technical assessments and organizational activities. The indicators are designed to predict how resilient the agency, its infrastructure, and its services will be when faced with a natural hazard event. The indicators are not designed to provide information on which investments in improving resilience will have the greatest net benefits.

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[25] SDIA. 2020. *Climate Resilience Plan*, pp. 60–62.

[26] SDIA. 2020. *Climate Resilience Plan*, p. 46.

[27] SDIA. 2020. *Climate Resilience Plan*, p. 46.

The agency produced its first organization-wide "Resilience Indicator Framework" in 2015[28] and in 2020 issued a significant update.[29] The agency built on a vulnerability assessment completed in 2014 and on a previous pilot project for transit indicators funded by FTA.[30] The agency selected the indicators after a review of research and best practices worldwide and adapted them to be specific to LACMTA's organization and practices.[31]

Table 3-1 lists the technical and organizational indicators as refined in 2020. Technical indicators evaluate the performance of physical systems. They can be used to evaluate a single asset or a group of assets that work together, such as the assets that make up the communication system or all of the stations along a rail line. Organizational indicators evaluate the capacity of the organization to make decisions and to act. Although evaluations of costs and benefits are not included, nothing precludes examining the costs and benefits of specific actions.[32]

TABLE 3-1 LACMTA Resilience Framework Updated Resilience Indicators[33]

Technical Indicators	Organizational Indicators
Robustness	**Information Management and Communication**
R-01. Maintenance – Day to Day	I-01. Warnings and Public Awareness
R-02. Maintenance – Post Incident	I-02. Communication Systems – Staff
R-03. Renewal/Upgrade (Long Range Plans)	I-03. External – Public Awareness
R-04. Design – Compliance with Current Codes	I-04. Sensors
R-05. Design – Condition of Asset	I-05. Data – Access to, and Maintenance of, Key Data Sets
R-06. Design – Vulnerability Assessment	I-06. Information Security and Contingency Planning
R-07. Design – Resilience Design Criteria	
R-08. Design – Overheating Standards	
R-09. Extreme Weather Repair Costs	
R-10. Supplier Utility Robustness – Awareness	
R-11. Supplier Utility Robustness – Improvement	

continued

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[28] LACMTA (Los Angeles Metropolitan Transportation Authority). 2015. "Resiliency Indicator Framework." http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf.

[29] LACMTA. 2020. "Resiliency Indicator Framework: 2020 Addendum." http://media.metro.net/2020/Addendum-to-Resiliency-Framework.pdf.

[30] FTA. 2013. *Los Angeles County Metropolitan Transportation Authority Climate Change Adaptation Pilot Project Report.* FTA Report No. 0073. https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_Report_No._0073.pdf.

[31] LACMTA. 2015. "Resiliency Indicator Framework." http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf.

[32] LACMTA. 2015. "Resiliency Indicator Framework." http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf.

[33] LACMTA. 2020. "Resiliency Indicator Framework: 2020 Addendum." http://media.metro.net/2020/Addendum-to-Resiliency-Framework.pdf.

TABLE 3-1 Continued

Technical Indicators	Organizational Indicators
Redundancy	**All Hazards Planning, Preparedness, and Response**
RE-01. Alternate Route/Mode Availability	A-01. Risk Assessment and Scenario Planning
RE-02. Alternate Route/Mode Capacity	A-02. Tracking Incident-Related Injuries
RE-03. Spare Capacity	A-03. Tracking Essential Resources
RE-04. Back Up Parts and Equipment	A-04. Priority Routes/Structures
RE-05. Re-routing and Communication Plans	A-05. Emergency Management Plans – Existence
RE-06. Supplier Utility Redundancy – Awareness	A-06. Joint Planning
RE-07. Supplier Utility Redundancy – Improvements	A-07. Training/Drills – Offered
	A-08. Training/Drills/Tests – Completed
	A-09. Lessons Learned and Thinking Ahead
	A-10. Critical Energy and Supply Chain Provision
	Financial Preparedness
	F-01. Insurance Coverage
	F-02. Insurance Information
	F-03. Capital Availability
	F-04. Operational Funding
	F-05. Contingency Funding
	F-06. Modelling
	Networks and Staffing
	N-01. Internal Relationships
	N-02. Information Sharing – Internal
	N-03. Inter-agency Compatibility
	N-04. Business Continuity/Awareness
	N-05. External Information Sharing and Cooperation
	N-06. Roles and Responsibilities Identified
	N-07. Remote Response Ability
	Leadership and Culture
	L-01. Resilience Is a Clear Priority of Metro Leadership
	L-02. Roles, Responsibilities, and Goals
	L-03. Staff Engagement and Leveraging Knowledge
	L-04. Crisis Decision Making
	L-05. Mid/Long Term Decision Making
	L-06. Advance Agreements
	L-07. Approach to Projects

Each indicator is accompanied by a grading rubric that describes a score from 1 to 4, with a score of 4 representing the highest level of resilience. For example, for the resilience design criteria indicator, the lowest score corresponds to no resilience design criteria and the highest score to "resilience design criteria have been developed and strategies have been implemented for new and upgrade/repair projects." For the alternative route/mode capacity indicator, the lowest score is assigned if the "alternate mode has <25% capacity of the failed mode during peak demand" and the highest score if the "alternate, unaffected mode has >75% capacity of failed mode during peak demand."[34] The 1–4 scores are then transformed into percentages to make them easier for the public to understand.

Although the 2015 framework focused only on extreme weather related to climate change, the 2020 update adopted an "all hazards" approach because "many actions needed to ensure resilience against climate change are the same ones needed to ensure resiliency against other hazards." The 2020 update applies to 11 natural hazards and nine human-caused threats, and all indicators are relevant to all hazards and threats.[35]

LACMTA's indicator framework can be used to track its progress over time and to evaluate the strengths and weaknesses of the agency's readiness for specific hazards. Scores for each principle are generated by averaging the scores of the principle's indicators. For example, given a scenario of an earthquake similar to 1994's Northridge earthquake, scores generated by using the indicator framework revealed that, among the organizational principles, LACMTA was strongest in Networks and Staffing and weakest in Information Management and Communication.[36]

An overall resilience score can be produced by averaging the scores of the seven principles. Although LACMTA experimented with weighting indicators and principles, the agency decided in the 2020 revision to weigh equally all indicators within each principle and all principles in the overall resilience score. It is notable that, of the seven principles, five relate to organizational indicators and only two to technical (i.e., infrastructure-related) indicators. Because the seven principles are weighted equally, 71% of the weight in the final resilience score is drawn from organizational indicators.

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[34] LACMTA. 2015. "Resiliency Indicator Framework," pp. 25, 27. http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf.

[35] LACMTA. 2020. "Resiliency Indicator Framework: 2020 Addendum," p. 2. http://media.metro.net/2020/Addendum-to-Resiliency-Framework.pdf.

[36] LACMTA. 2020. "Resiliency Indicator Framework: 2020 Addendum," pp. 10–11. http://media.metro.net/2020/Addendum-to-Resiliency-Framework.pdf.

DESIGN GUIDES

The practice of resilience is, for the most part, still in the stages of customized analysis and application experimentation. Design guides are one example of how resilience may become part of the routine practices of transportation agencies.

Many resilience plans call for mitigation or adaptation practices to be institutionalized as part of design guides. Especially for smaller projects, design guides may also reduce the need to conduct resilience analysis on a project-by-project basis. The *Climate Resilience Design Guidelines* from the engineering department of The Port Authority of New York and New Jersey standardizes the agency's response to sea level rise and storm surge, using the requirements in the respective state building codes and augmenting them as needed. The design guide sets elevation standards, in inches, depending on the probability of the flood hazard, whether the asset is deemed critical or non-critical in the building codes or in the Port Authority's own assessment, and the asset's design life.[37]

New York City's *Climate Resiliency Design Guidelines* prepare public investments for future climate change by standardizing resilient design criteria across the city's wide portfolio of assets. By means of local law, these guidelines have been recently mandated for all capital projects in New York City. The guidelines translate localized climate projections for heat, precipitation, and sea level rise into data sets that can be used by project designers (see Table 3-2 below for guidance on engineering with future heat conditions) based on the project's useful life and criticality. The guidelines also provide tools for project managers to assist in resilient design decision making, such as risk assessment methodology and BCA, that are scalable based on the project size. For likelihood of the natural hazard, the guidelines instruct users to assign a rating to hazards on a qualitative scale from rare to nearly certain. Similarly, consequences are to be summarized on the scale of minor, moderate, and severe. The product of likelihood and consequences is called the "risk rating matrix." To choose resilient designs above and beyond those required by building codes, the guidelines advise conducting a qualitative assessment of benefits for capital projects under \$50 million. Quantitative, detailed BCA is reserved for projects that have more than \$50 million in total costs.[38]

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[37] The Port Authority of New York and New Jersey. 2018. *Climate Resilience Design Guidelines*. https://www.panynj.gov/business-opportunities/pdf/discipline-guidelines/climate-resilience.pdf.

[38] New York City Mayor's Office of Recovery and Resilience. 2019. *Climate Resiliency Design Guidelines: Version 3.0.*

TABLE 3-2 New York City *Climate Resiliency Design Guidelines* Climate Change Data for Designing with Future Heat Conditions

	Extreme Heat Events			Design Criteria	
End of Useful Life	**# of Heat Waves per Year**	**# of Days at or Above 90°F**	**Annual Average Temperature**	**1% Dry Bulb Temperature**	**Cooling Degree Days (Base –65°F)**
Historic trend (1971–2000)	2	18	54°F	91°F	1,149
2020s (through 2039)	4	33	57.2°F	—	—
2050s (2040–2069)	7	57	60.6°F	98°F	2,149
2080s (2070–2099)	9	87	64.3°F	—	—

NOTES: Due to heating, ventilation, and air conditioning system typical useful life of around 25 years, only design criteria projections for the 2050s are shown. Projections for the 2020s are not shown because it is anticipated that enough of a safety margin is employed already in current systems to withstand the temperature rise expected through the 2020s. The Northeast Power Coordinating Council is developing projections of 1% wet bulb temperatures, which are expected to increase. This design criteria will be added in a later version of the guidelines.
SOURCE: City of New York. 2019. The table data were provided with the permission of the City of New York.

SUMMARY OF METRICS

This section presents a table of metrics that some transportation agencies are using (see Table 3-3). The table shows the output measures that agencies use to make decisions on resilience improvements, the intermediate measures that they use to calculate the output measures, and a few examples of the input data used to calculate the intermediate measures.

TABLE 3-3 Summary of Resilience Measures Used by Transportation Agencies

Output Measures	Intermediate Measures	Input Data
Annual Risk (Colorado DOT)	Hazard probability	Probability of rockfalls
		Probability of floods
		Probability of debris flows
	Vulnerability	Engineering judgment
	Consequences	Repair costs to Colorado DOT
		Number of days highway closed
		Length of detour required
		Lost wages and truck revenues
Risk Value (Utah DOT)	Hazard probability	Flood probability
		Rockfall probability
		Avalanche probability
		Debris flow probability
		Earthquake probability
	Consequences	Repair costs to Utah DOT
		Length of detours
		Hourly value of time
		Hourly vehicle operating costs
Level of Resilience (Colorado DOT)	Annual risk (see above)	
	Criticality	Freight value
		Tourism value
		SoVI®
Risk Priority (Utah DOT)	Risk value (see above)	
	Criticality	Road network redundancy
		Average annual daily traffic
		Truck average daily traffic

TABLE 3-3 Continued

Output Measures	Intermediate Measures	Input Data
Vulnerability (San Diego International Airport)	Exposure	Annual number of days of extreme heat
		Area exposed to flooding 95th percentile risk of sea level rise
	Consequences	Asset damage
		Service disruption
		Job loss
		Life safety consequences
		Bird habitat damage
Resilience Indicators (LACMTA)	Robustness	Design – Vulnerability assessment
	Redundancy	Back-up parts and equipment
	Information management and communication	Warnings and public awareness
	All hazards planning, preparedness, and response	Tracking essential resources
	Financial preparedness	Capital availability
	Leadership and culture	Crisis decision making
Design Guide (The Port Authority of New York and New Jersey)	Hazard probability	Projected sea level rise
		Projected precipitation increase Projected temperature increase
	Asset service life	Number of years before asset is expected to be replaced
	Asset criticality	Classification of asset into "critical" or "non-critical" categories
Design Guide (New York City)	Hazard probability	Projected temperature increase
		Projected precipitation increase
		Projected sea level rise
	Consequences	Damage to facility
		Damage to surrounding community
	Asset useful life	Durability of asset
		Replaceability of asset
	Asset criticality	Services provided
		Importance in emergency

continued

TABLE 3-3 Continued

Output Measures	Intermediate Measures	Input Data
Net Benefits of Resilience Improvements (Colorado DOT)	Annual risk without improvement	
	Annual risk with improvement	
	Costs of improvements	
Net Benefits of Resilience Improvements (Utah DOT)	Risk priority (see above)	
	Costs of improvements	
Net Benefits of Resilience Improvements (HRTPO)	Hazard probability	Flood risk
	Vulnerability	Effects of floods on roads, bridges, and tunnels
	Consequences	Wider economic impacts of transportation disruptions
Net Benefits of Resilience Improvements (New York City)	Direct benefits	Quantitative analysis for projects >$50 million
	Indirect benefits	Qualitative analysis for projects <$50 million
	Other benefits	
	Costs	

NOTE: The input data shown are just a few examples of the input data used by each agency.

CHAPTER SUMMARY

The review of current practice found that transportation agencies are progressing in their adoption of analysis, planning, and management practices for addressing resilience. Agencies are primarily integrating resilience into their planning and management practices because of past harms from hazard events, as well as federal and state mandates and incentives. Adoption remains uneven, however, and the agencies that do engage in resilience analysis use a variety of methodologies and metrics tailored to the specific infrastructure and services that the agencies provide, as well as agency goals. There is no common set of resilience metrics.

The resilience analysis and planning methods used by transportation agencies contain common elements. Agencies analyze hazard likelihood and characterization to assess the vulnerability of their assets, networks, and services. They use vulnerability and criticality assessments to prioritize subsequent studies of mitigation actions. They conduct assessments of consequences to gain an understanding of the impacts of failing to act in the face of climate change. Agencies differ, however, in their use of quantitative analyses, especially monetary assessments of risk in terms of expected losses. Although vulnerability assessments are becoming an established practice, with methods piloted and disseminated by U.S. DOT, many agencies still rely on indicators or qualitative descriptors for their analysis of consequences. Tools and practices that foster formal assessments of risk for the status quo and for the reduction of risk from investments in resilience are still in the developmental stage.

The analytical approaches described in this chapter are used by agencies for a variety of purposes. The majority are used to support decision making at the planning and project level. Outcomes from these analyses are also applied to asset management, maintenance operations, and post-disaster responses and restoration efforts.

4

Contemporary Research on Resilience and Resilience Metrics

In 2013 the White House defined resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption," adding that "resilience includes the ability to *withstand* and *recover* from deliberate attacks, accidents, or naturally occurring threats or incidents."[1]

The first formal definition of resilience was provided in 1973 and focused on the ability of a system to absorb unusual disturbances and remain functional.[2] Over the years, many other definitions of resilience have been proposed in science and engineering.[3,4] Likewise, the field of resilience research has diversified into several areas of study (see Box 4-1). Despite the variety of approaches, resilience research has emphasized two important features: the inclusion of the post-event recovery phase and the use of functionality—at the component and system levels—as the primary framework for analysis. Most resilience metrics used in research relate to the "functionality recovery

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[1] The White House. 2013. Presidential Policy Directive—Critical Infrastructure Security and Resilience. PPD-21. http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

[2] Holling, C.S. 1973. "Resilience and Stability of Ecological Systems." *Annual Review of Ecology and Systematics* 4:1–23. https://doi.org/10.1146/annurev.es.04.110173.000245.

[3] Bruneau, M., S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, and D.V. Winterfeldt. 2003. "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra* 19:733–752.

[4] Bocchini, P., D.M. Frangopol, T. Ummenhofer, and T. Zinke. 2014. "Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach." *Journal of Infrastructure Systems* 20:04014004. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000177.

BOX 4-1
Areas of Resilience Research

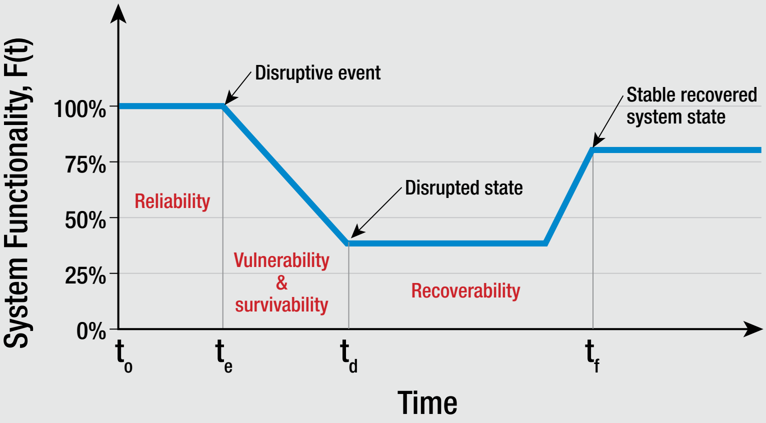
Resilience research of the decline in functionality after disruptive events is divided into four different types of academic studies: system reliability, vulnerability, survivability, and recoverability.

Reliability—Research on reliability is useful in transportation resilience as a way to understand the occurrence of a hazard or disruptive event and the time interval between disruptions. When disruptive events are of a stochastic nature, research in reliability theory provides methods and techniques to analyze, model, and optimize system behavior.[a]

Vulnerability—Current vulnerability research is developing approaches that describe the interaction between a disruptive event and system performance so as to quantify the degradation of specific system components and their functions.[b] The aim is to identify the system elements that generate the highest damage when disrupted. These elements are known as points of system vulnerability.

Survivability—Survivability focuses on techniques that maintain system service continuity in the face of potential disruptive events. Research in survivability develops approaches that can help the system become robust through adaptability (i.e., ability to change the system so it can perform for new requirements) and flexibility (i.e., ability to adapt to a range of adverse events without having to anticipate the particular response in advance).[c] Although research on survivability typically examines telecommunications systems, the similarities between transportation systems and telecommunication services makes the research applicable to transportation as well.

Recoverability—Research in recoverability deepens understanding of the ability of systems to recover after a disruptive damaging event. For example, Rose describes dynamic recoverability as related to “the speed at which an entity or system recovers from a severe shock to achieve a desired state.”[d] While there are many studies related to recoverability, especially in socioecological or sociotechnical resilience, most are management or lessons-learned oriented and thus generally unquantifiable. Moreover, except for the analysis presented for intermodal freight systems by a few researchers, there is a void in research related to the stochastic behavior of recovery in general networked systems.[e]



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[a] Elsayed, E.A. 2012. *Reliability Engineering.* Hoboken, New Jersey: John Wiley & Sons.

[b] Crucitti, P., V. Latorak, W. Ebeling, and B. Spagnolo. 2005. “Locating Critical Lines in High-Voltage Electric Power Grids.” *Fluctuation and Noise Letters* 5(2):L201–L208. https://doi.org/10.1142/S0219477505002562; Zhang, S., D. Caragea, and X. Ou. 2011. “An Empirical Study on Using the National Vulnerability Database to Predict Software Vulnerabilities.” *Database and Expert Systems Applications* 6860. https://link.springer.com/chapter/10.1007/978-3-642-23088-2_15; Nagurney, A., and Q. Qiang. 2008. “An Efficiency Measure for Dynamic Networks Modeled as Evolutionary Variational Inequalities with Application to the Internet and Vulnerability Analysis.” *Netnomics* 9:1–20. https://doi.org/10.1007/s11066-008-9008-z; Zio, E., G. Sansavini, R. Maja, and G. Marchionni. 2008. “An Analytical Approach to the Safety of Road Networks.” *International Journal of Reliability, Quality and Safety Engineering* 15(1):67–76. https://www.worldscientific.com/doi/abs/10.1142/s0218539308002939.

[c] Westmark, V.R. 2004. “A Definition for Information System Survivability.” *Proceedings of the 37th Annual Hawaii International Conference on System Sciences, 2004.* https://doi.org/10.1109/HICSS.2004.1265710.

[d] Rose, A. 2007. “Economic Resilience to Natural and Man-Made Disasters: Multi-Disciplinary Origins and Contextual Dimensions.” *Environmental Hazards* 7(4):383–398. https://doi.org/10.1016/j.envhaz.2007.10.001.

[e] Nair, R., H. Avetisyan, and E. Miller-Hooks. 2010. “Resilience Framework for Ports and Other Intermodal Components.” *Transportation Research Record* 2166(1):54–65. https://doi.org/10.3141/2166-07; Ta, C., A.V. Goodchild, and K. Pitera. 2009. “Structuring a Definition of Resilience for the Freight Transportation System.” *Transportation Research Record* 2097(1):19–25. https://doi.org/10.3141/2097-03; Pant, R., K. Barker, F. Grant, and T. Landers. 2011. “Interdependent Impacts of Inoperability at Multi-Modal Transportation Container Terminals.” *Transportation Research Part E: Logistics and Transportation Review* 47:722–737. https://doi.org/10.1016/j.tre.2011.02.009.

curve," which describes the evolution of functionality (or performance or level of service) over time after a disruptive event.[5]

The approach to resilience presented in this chapter builds on research into safety, reliability, and risk. Metrics related to safety and reliability account for the hazard and the probability of a component/system falling below a performance threshold, and risk-based metrics consider the consequences associated with performance failures. Resilience-related metrics are used to examine when and how a system can maintain or regain its ability to function after a disruptive event and account for a system's inherent coping capacity and adaptability. Figure 4-1 describes this approach, connecting safety and reliability, risk, and resilience.

The research literature reviewed here uses functionality recovery curves and their associated metrics to measure resilience. Although resilience metrics based on functionality recovery curves are not yet in common practice and more research is needed in some areas, the foundational concepts represented by functionality recovery curves and their metrics are useful for framing the analysis of transportation's resilience to natural hazards. In addition, the metrics required by functionality recovery curves will often be useful to conduct the analysis outlined in the framework presented in Chapter 5.

This chapter begins with an introduction to functionality recovery curves and how they are used to measure resilience. To apply functionality recovery curves to transportation, the chapter provides an overview of fragility curves and transportation-specific functionality metrics. The results of a comprehensive review of functionality metrics for the surface, air, and water modes are provided in Table 4-2 at the end of the chapter. Because the analysis of natural hazards requires methods to deal with uncertainty, the chapter also covers probabilistic approaches to functionality recovery curves and resilience metrics. The chapter concludes with research on tools that are useful for analyzing investments that are intended to increase the resilience of transportation systems.

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[5] Sun, W., P. Bocchini, and B.D. Davison. 2020. "Resilience Metrics and Measurement Methods for Transportation Infrastructure: The State of the Art." *Sustainable and Resilient Infrastructure* 5:168–199. https://doi.org/10.1080/23789689.2018.1448663.

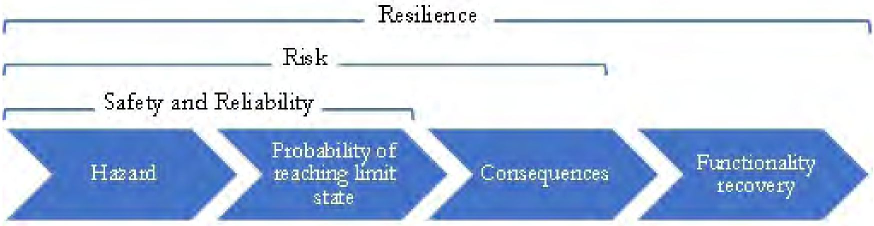

FIGURE 4-1 Relationship among safety and reliability, risk, and resilience.[6]

FUNCTIONALITY RECOVERY CURVES

The resilience of a transportation system is related to its functionality during and after a harmful event. A common way to illustrate a system's resilience is to represent its functionality (or performance or level of service) over time with a functionality recovery curve. Functionality recovery curves can be applied to almost any system and any disruption. For an electric utility after a hurricane, functionality could be measured as a percentage of power demand satisfied over time. For a school district during a pandemic, functionality could be measured as the number of student-hours delivered over time.

To apply functionality recovery curves to transportation, the analyst must first select the metrics that best describe the important functions of the system under study. For a given transportation system, multiple metrics may be required to fully describe its services. For example, the carried and crossed traffic flow capacities of a bridge are two different metrics that can evolve differently over time, generating two different functionality recovery curves. For a transportation network, some metrics focus on the traffic flow capacity (e.g., traffic volumes or tons of freight moved per time period) and others capture the degree of connectedness (e.g., number or types of places connected).[7,8] Therefore, when performing a resilience assessment, multiple functionality recovery curves may be needed, each capturing different aspects of the system functionality and each generating a different value of the resilience metric associated with performance during the event and recovery.

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[6] Bocchini, P. 2021. "Regional-Level Approach to Resilience Assessment." NIST (National Institute of Standards and Technology) Center of Excellence Seminar Series, Colorado State University, March 25. http://resilience.colostate.edu/seminar/Paolo-Bocchini%202.mp4.

[7] Faturechi, R., and E. Miller-Hooks. 2015. "Measuring the Performance of Transportation Infrastructure Systems in Disasters: A Comprehensive Review." *Journal of Infrastructure Systems* 21(1):04014025. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000212.

[8] Zhang, X., E. Miller-Hooks, and K. Denny. 2015. "Assessing the Role of Network Topology in Resilience of Transportation Systems." *Journal of Transport Geography* 46:35–45.

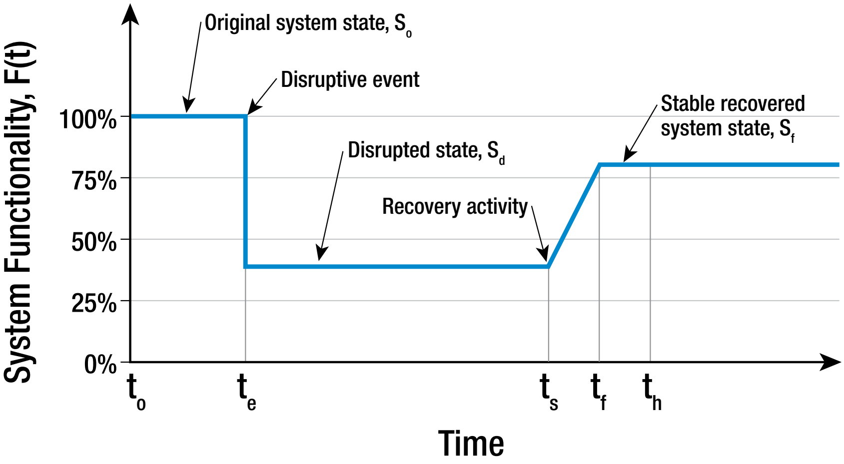

FIGURE 4-2 General functionality recovery curve.

Figure 4-2 presents an example of a functionality recovery curve, where time (t)—typically measured starting from the occurrence of the first disruption—is represented in the horizontal axis, and a metric representing the functionality of the component/system under study, $F(t)$, is presented in the vertical axis. When the system is disrupted, the system's functionality shifts from its original state, S_0, to a disrupted state, S_d. Functionality remains in its disrupted state for a period of time until recovery activity begins. Eventually, recovery activity yields a stable system state, S_f.

The stable, recovered system state may not be at the same level of functionality as the original state. For instance, in Figure 4-2, functionality after recovery is flat at a level that is worse than its performance before the disruptive event. However, in recent years there has been a strong push to leverage the post-disaster recovery and reconstruction period to build more resilient and better performing systems. The United Nations has formally promoted this approach since 2015 in its *Sendai Framework for Disaster Risk Reduction* under the "Build Back Better" motto.[9]

In Figure 4-2, there are four notable time points on the horizontal axis of the functionality recovery curve: the time when the disruptive event starts (t_e), the time when the maximum disrupted functionality first occurs (t_d), the time recovery activity commences (t_s), and the time of achieving the stable, recovered state (t_f). When the impact on functionality is nearly

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[9] United Nations. 2015. *Sendai Framework for Disaster Risk Reduction 2015–2030*. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

instantaneous, like earthquakes, t_e and t_d occur nearly simultaneously. For events such as hurricanes or wildfires, however, the loss of functionality may occur more gradually over an interval of time. Figure 4-2 illustrates the gradual loss of functionality with a decreasing curve from the time of the event to the time when the maximum disrupted functionality, (t_d), first occurs.[10] Finally, t_h represents the extent of the time horizon of the analysis, which is set by the analyst and used to standardize some popular resilience metrics.[11,12,13]

During the recovery process, improvements in functionality may happen in fits and starts and functionality may even temporarily worsen. For example, a partially functioning bridge may need to be closed for repairs. In addition, recent studies have challenged the practice of setting the pre-event functionality level at 100%. Instead, pre-event functionality varies. Functionality as designed or built (at t_0) is set to 100% and then decreases (or jumps around) due to aging, deterioration, demand, environmental factors (including climate change stressors), maintenance, and other disruptions. Thus, the functionality at the time of the event may be less than 100%. Figure 4-3 illustrates both pre-event deterioration of functionality and nonlinear recovery.[14]

Performance at the system level is usually the most important result for resilience planning and society. A system-level performance model uses the functionality recovery curves of individual components to calculate the functionality recovery curve for the system.[15] Functionality recovery curves can take many shapes. For complex systems, such as a transit system,

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[10] Henry, D., and J.E. Ramirez-Marquez. 2012. "Generic Metrics and Quantitative Approaches for System Resilience as a Function of Time." *Reliability Engineering and System Safety* 99(1):114–122.

[11] Reed, D.A., K.C. Kapur, and R.D. Christie. 2009. "Methodology for Assessing the Resilience of Networked Infrastructure." *IEEE Systems Journal* 3:174–180. https://doi.org/10.1109/JSYST.2009.2017396.

[12] Frangopol, D.M., and P. Bocchini. 2011. "Resilience as Optimization Criterion for the Rehabilitation of Bridges Belonging to a Transportation Network Subject to Earthquake." In *Proceedings of the 2011 Structures Congress* (D. Ames, T.L. Droessler, and M. Hoit, eds.). Las Vegas, Nevada: ASCE. April 14–16, pp. 2044–2055. https://doi.org/10.1061/41171(401)178.

[13] Faturechi, R., and E. Miller-Hooks. 2014. "Mathematical Framework for Quantifying and Optimizing Protective Actions for Civil Infrastructure Systems." *Computer-Aided Civil and Infrastructure Engineering Systems: Special Issue on Sustainability and Resilience of Spatially Distributed Civil Infrastructure Systems* 29:572–589.

[14] Levenberg, E., E. Miller-Hooks, A. Asadabadi and R. Faturechi. 2016. "Resilience of Networked Infrastructure with Evolving Component Conditions." *ASCE Journal of Computing in Civil Engineering* 31(3). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000629.

[15] Karamlou, A., and P. Bocchini. 2017. "From Component Damage to System-Level Probabilistic Restoration Functions for a Damaged Bridge." *Journal of Infrastructure Systems* 23(3). https://doi.org/10.1061/(ASCE)IS.1943-555X.0000342.

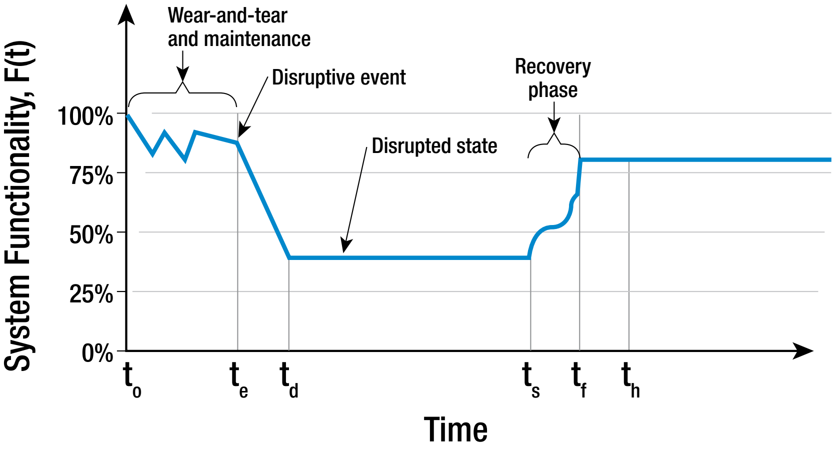

FIGURE 4-3 Resilience curve illustrating non-uniform, pre-event system performance due to component deterioration and maintenance actions and nonlinear recovery phase.

they tend to be continuous curves,[16] which can be modeled analytically[17] or through experimental observations and post-event measurements. For individual components, a functionality measure may only have a small set of discrete values (e.g., number of open lanes in a bridge) or be binary (e.g., a traffic light is working or not working).[18]

RESILIENCE METRICS BASED ON FUNCTIONALITY RECOVERY CURVES

Because functionality recovery curves condense information about the resilience of a system, they can be applied to a wide range of assets, systems, and types of disruptions. Although the measures of functionality need to be

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[16] Continuity is due to the fact that complex systems typically have a large set of possible functionality levels, so recovery curves tend to vary in a gradual way. For instance, the total travel time over a rush hour is affected by a multitude of factors, and each road closure/opening has a tiny impact on it. A simple system, instead, has a much simpler set of possible states (often only two—functional or not), so the functionality curve shifts from one state to the other. For instance, a small, single lane bridge is either closed or open, so the functionality shifts from 0 to 1.

[17] Decò, A., P. Bocchini, and D.M. Frangopol. 2013. "A Probabilistic Approach for the Prediction of Seismic Resilience of Bridges." *Earthquake Engineering and Structural Dynamics* 42(10):1469–1487. https://doi.org/10.1002/eqe.2282.

[18] Padgett, J.E., and R. DesRoches. 2007. "Bridge Functionality Relationships for Improved Seismic Risk Assessment of Transportation Networks." *Earthquake Spectra* 23:115–130.

specific for each system, the associated resilience metrics can be defined in a general way and are said to be "event agnostic" and "system (or mode) agnostic." It is important to stress again that functionality metrics need to be specific to the area being studied, the mode of transportation, and in some cases even the hazard scenario. When appropriate, multiple functionality metrics may be needed to capture the performance of an asset/system. On the other hand, the resilience metrics discussed in this section are general enough to be applicable to virtually any asset, system, region, mode of transportation, and hazard.

Resilience Index

A commonly used resilience metric is called the "resilience index," F_{mean}, and it is simply the mean value of functionality during the time horizon of analysis, which starts with the beginning of the perturbative event at t_e and lasts to a time t_h defined by the analyst in such a way as to include the recovery phase.[19] The resilience index can be also seen as the normalized (over time) area under the functionality recovery curve (see Figure 4-4).

The resilience index has the advantage of being easy to assess and interpret, while also capturing different aspects of resilience. For example, a system will have a high resilience index if it is capable of preserving a high level of functionality after the disruptive event. Similarly, the resilience index is high if a system suffers a substantial functionality loss but recovers very quickly.

Resilience Triangle

The "resilience triangle" measures the total loss of functionality from the time of the event to the end of the recovery process. Bruneau and colleagues defined "robustness" as the amount of residual functionality after the initial drop, "rapidity" as the average slope of the functionality recovery curve during the recovery phase, and the "resilience triangle" (see Figure 4-5) as the area over the recovery curve that is representative of the loss of functionality.[20]

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[19] Reed, D.A., K.C. Kapur, and R.D. Christie. 2009. "Methodology for Assessing the Resilience of Networked Infrastructure." *IEEE Systems Journal* 3:174–180. https://doi.org/10.1109/JSYST.2009.2017396.

[20] Bruneau, M., S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, and D.V. Winterfeldt. 2003. "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra* 19:733–752.

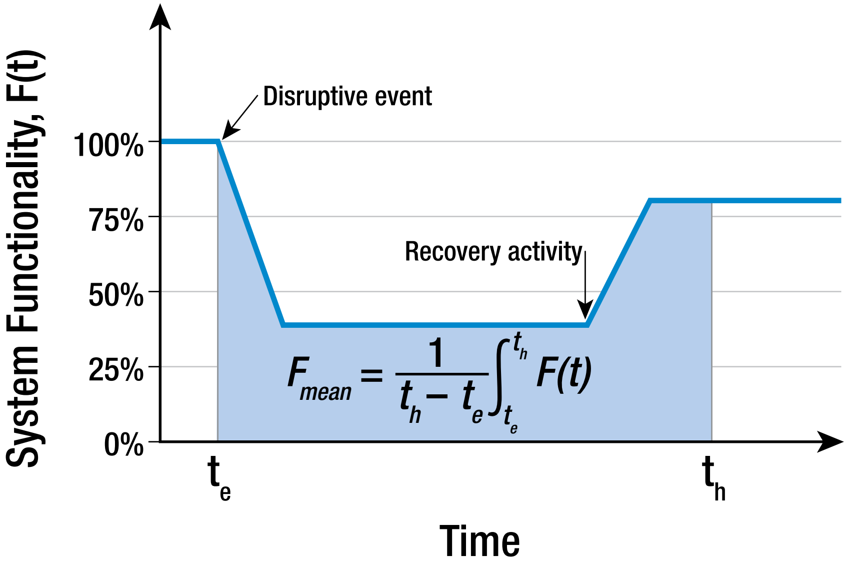

FIGURE 4-4 Representation of resilience index as the normalized area under the functionality recovery curve.

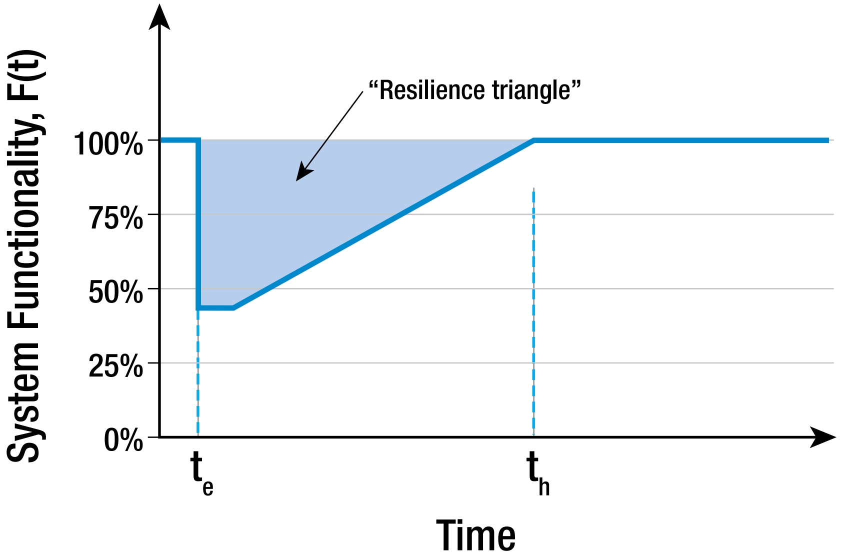

FIGURE 4-5 Illustration of the concept of "resilience triangle."

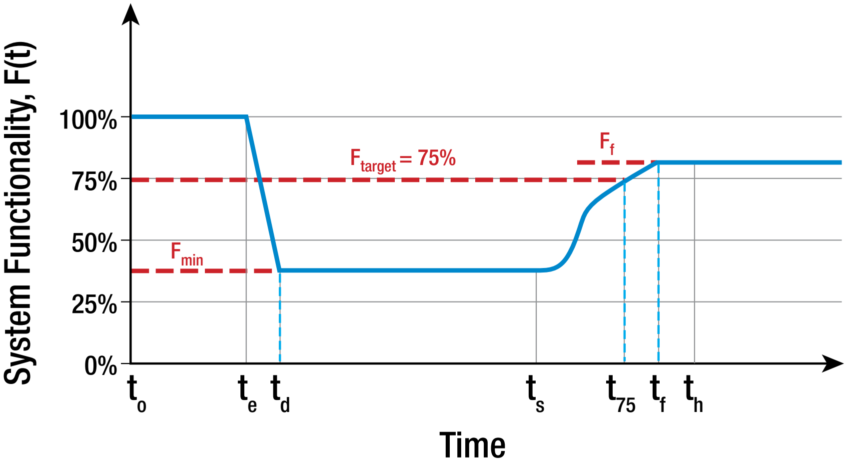

FIGURE 4-6 Example of a functionality recovery curve that includes the resilience metrics "minimum level of functionality" (F_{min}), "level of functionality restored at the end of the recovery process" (F_f), and "time to reach a target level of functionality" (F_{target}).

Other Functionality-Based Metrics

There are additional resilience metrics that represent variations on functionality. For example, the minimum level of functionality at any time during the recovery, F_{min}, is a useful metric for analyzing the worst-case scenario (see Figure 4-6). Similarly, the level of functionality restored at the end of the recovery process, F_f, can be used to represent the degree of reparability of the system and, indirectly, the resourcefulness of the operator.

Time to Complete Recovery

An even simpler metric is the "time to complete recovery." While this metric is appealing because of its simplicity, it conveys only limited information about the severity of the loss of functionality and the path to recovery. Moreover, for systems that never recover to 100% of their pre-event functionality, the metric would remain undefined. It is also important to differentiate between public recovery (i.e., when services are partially or fully restored) and full recovery (i.e., when the systems are restored to their original functionality or enhanced). While public recovery can be accomplished within days, weeks, or months, full recovery often entails longer terms.

Time to Reach a Target Level of Functionality

Metrics for "time to reach a target level of functionality" report the time to reach a level of functionality that is less than 100% but still an important threshold. In Figure 4-6, the target functionality, F_{target}, is 75%, and t_{75} corresponds to the point in time when recovery activities have restored functionality to 75%. In addition to being useful in cases where recovery never reaches 100% of pre-event functionality, this type of metric can be particularly relevant to disaster management planning and reporting.

For example, the San Francisco Planning and Urban Research Association (SPUR) introduced and popularized the concept of "resilience tables" that use time to target functionality metrics. In Table 4-1, each row of the resilience table lists a community facility, type of infrastructure, or critical system and a target level of functionality (e.g., 90% of roads and highways). The columns represent time, and the resulting matrix identifies both the official goal of local disaster response planning (shaded areas) and SPUR's assessment of current recovery time (marked "X").[21]

More generally, this metric is useful for analyzing gaps between the desired time to reach a target level of functionality set by policy makers and the estimate produced by engineers and planners of the most likely time to reach the target. The discrepancy between the desired and the most likely times can be used to assess which assets or locations are most in need of mitigation actions. This gap analysis has been used in numerous resilience assessments done by state and local governments.[22,23,24]

Metrics for Recovery Activities

Functionality recovery curves can also be used to analyze the impact of actions designed to increase resilience. The curves can assess actions to be taken before or during an event and during the recovery activity phase. In Figure 4-7, the dotted line at the bottom illustrates the baseline resilience

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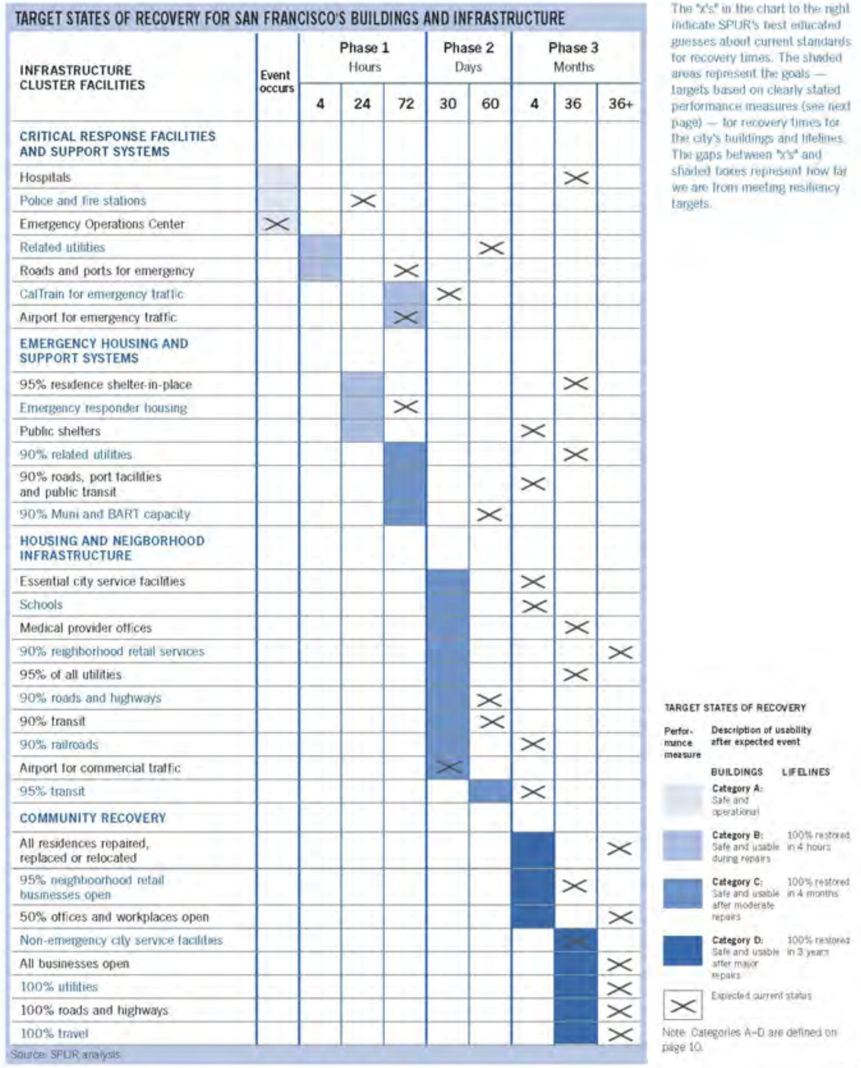
[21] Poland, C.D. 2009. *The Resilient City: Defining What San Francisco Needs from Its Seismic Mitigation Policies.* San Francisco, CA: San Francisco Planning and Urban Research Association.

[22] Oregon Seismic Safety Policy Advisory Commission. 2013. *Oregon Resilience Plan.* https://www.oregon.gov/oem/documents/oregon_resilience_plan_final.pdf.

[23] Washington State Emergency Management Council: Seismic Safety Committee. 2012. *Resilient Washington State—A Framework for Minimizing Loss and Improving Statewide Recovery After an Earthquake.* https://mil.wa.gov/asset/5bac1790e2d29#:~:text=THE%20RESILIENT%20WASHINGTON%20STATE%20INITIATIVE,-This%20report%20is&text=The%20initiative%20was%20spearheaded%20by,before%20the%20next%20damaging%20event.

[24] NIST (National Institute of Standards and Technology). 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems.* https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1190v2.pdf.

TABLE 4-1 SPUR Model of Measuring Recovery from Earthquakes[25]



TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

INFRASTRUCTURE CLUSTER FACILITIES	**Event occurs**	**Phase 1** Hours			**Phase 2** Days		**Phase 3** Months		
		4	**24**	**72**	**30**	**60**	**4**	**36**	**36+**
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals	░							X	
Police and fire stations	░		X						
Emergency Operations Center	░ X								
Related utilities		▒				X			
Roads and ports for emergency		▒		X					
CalTrain for emergency traffic				▒	X				
Airport for emergency traffic				▒ X					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place			▒					X	
Emergency responder housing			▒	X					
Public shelters			▒				X		
90% related utilities				▓				X	
90% roads, port facilities and public transit				▓			X		
90% Muni and BART capacity				▓		X			
HOUSING AND NEIGBORHOOD INFRASTRUCTURE									
Essential city service facilities					▓		X		
Schools					▓		X		
Medical provider offices					▓			X	
90% neighborhood retail services					▓				X
95% of all utilities					▓			X	
90% roads and highways					▓	X			
90% transit					▓	X			
90% railroads					▓		X		
Airport for commercial traffic					▓ X				
95% transit						▓	X		
COMMUNITY RECOVERY									
All residences repaired, replaced or relocated							█		X
95% neighboorhood retail businesses open							█	X	
50% offices and workplaces open							█		X
Non-emergency city service facilities								█ X	
All businesses open								█	X
100% utilities								█	X
100% roads and highways								█	X
100% travel								█	X

Source: SPUR analysis

The "x's" in the chart to the right indicate SPUR's best educated guesses about current standards for recovery times. The shaded areas represent the goals — targets based on clearly stated performance measures (see next page) — for recovery times for the city's buildings and lifelines. The gaps between "x's" and shaded boxes represent how far we are from meeting resiliency targets.

TARGET STATES OF RECOVERY

Perfor-mance measure	**Description of usability after expected event**	
	BUILDINGS	**LIFELINES**
░	**Category A:** Safe and operational	
▒	**Category B:** Safe and usable during repairs	100% restored in 4 hours
▓	**Category C:** Safe and usable after moderate repairs	100% restored in 4 months
█	**Category D:** Safe and usable after major repairs	100% restored in 3 years
X	Expected current status	

Note: Categories A–D are defined on page 10.

made up of the inherent coping capacity of the asset (or system) and baseline recovery response activities. The three top curves indicate the changes to functionality recovery from adding redundancy, retrofitting to reduce the

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[25] Poland, C. 2009. "Defining Resilience: What San Francisco Needs from Its Seismic Mitigation Policies." *The Urbanist* 479. https://www.spur.org/publications/spur-report/2009-02-01/defining-resilience.

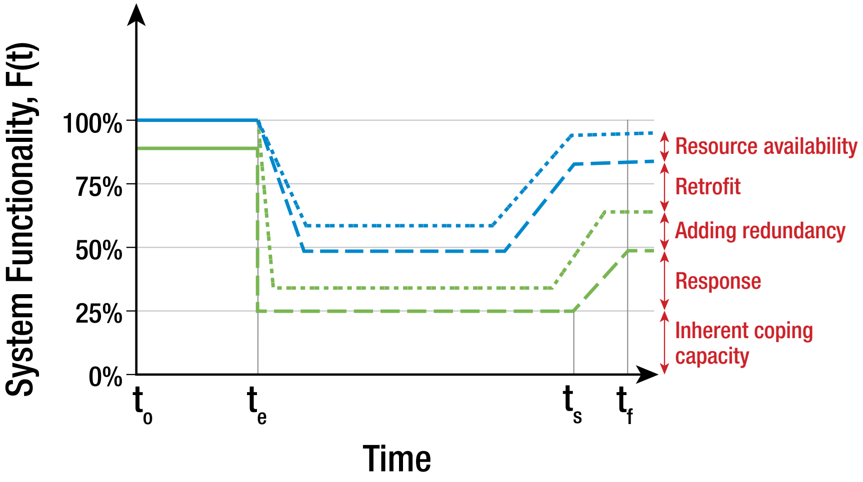

FIGURE 4-7 Illustration of the contribution to resilience from different actions: retrofitting, adding redundancy, providing effective recovery response, and increasing the resources available for recovery activities.[26]

vulnerability of components or assets, and increasing the resources available for recovery response activities.

MODELS INCORPORATING UNCERTAINTY

The metrics discussed in the previous section are deterministic—they do not account for randomness. Because uncertainty is a significant part of natural hazard analysis and resilience assessments, analysis approaches and metrics have been developed that address these uncertainties.

Significant uncertainties for measuring resilience are (1) what hazards will strike the assets in the future and (2) how the assets will respond. The first will gradually be reduced as the future climate reveals itself over time and as climate prediction models continue to improve. The second—the uncertainty in the performance of infrastructure systems—will be reduced with research on system performance in the face of hazards, including learning from natural experiments as we observe the performance of real systems in the face of natural hazards. Relevant current approaches are presented here.

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[26] Adapted from Faturechi, R., and E. Miller-Hooks. 2014. "Mathematical Framework for Quantifying and Optimizing Protective Actions for Civil Infrastructure Systems." *Computer-Aided Civil and Infrastructure Engineering Systems: Special Issue on Sustainability and Resilience of Spatially Distributed Civil Infrastructure Systems* 29:572–589.

Probabilistic hazard analysis is the science that studies the exposure of a region to hazards and assesses the probability of hazard events occurring and of reaching a certain level of intensity at each site.[27,28,29] For transportation systems, it is important to know both the probability of exceeding a certain intensity level at each site and the probability of having a certain intensity occur simultaneously at various locations of the system. For this reason, the science of scenario selection was developed to pick specific extreme event scenarios in a way that is representative of all of the possible scenarios that a hazard source can generate.[30,31,32,33]

For a given scenario, the damage and recovery process also includes large amounts of uncertainty. For instance, for a given level of ground shaking, the probability that a specific earthquake leads a bridge to collapse depends on the duration and frequency content of the earthquake, as well as the materials (random to some extent) used in its construction, the potential for imperfections in the construction phase, and the deterioration that the bridge has suffered over time. For transportation systems, these uncertainties can be captured using fragility curves that describe the probability of a component or system falling below a specified performance threshold for a given level of hazard intensity.[34,35,36] Similarly, vulnerability

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[27] McGuire, R.K. 2008. "Probabilistic Seismic Hazard Analysis: Early History." *Earthquake Engineering and Structural Dynamics* 37:329–338. https://doi.org/10.1002/eqe.765.

[28] Han, Y., and R.A. Davidson. 2012. "Probabilistic Seismic Hazard Analysis for Spatially Distributed Infrastructure." *Earthquake Engineering and Structural Dynamics* 41:2141–2158.

[29] Baker, J.W. 2008. *An Introduction to Probabilistic Seismic Hazard Analysis (PSHA).* https://www.jackwbaker.com/Publications/Baker_(2013)_Intro_to_PSHA_v2.pdf.

[30] Christou, V., P. Bocchini, M.J. Miranda, and A. Karamlou. 2017. "Effective Sampling of Spatially Correlated Intensity Maps Using Hazard Quantization: Application to Seismic Events." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 4(1):1–13.

[31] Manzour, H., R.A. Davidson, N. Horspool, and L.K. Nozick. 2016. "Seismic Hazard and Loss Analysis for Spatially Distributed Infrastructure in Christchurch, New Zealand." *Earthquake Spectra* 32:697–712. https://doi.org/10.1193/041415eqs054m.

[32] Jayaram, N., and J.W. Baker. 2009. "Correlation Model for Spatially Distributed Ground-Motion Intensities." *Earthquake Engineering and Structural Dynamics* 38:1687–1708. https://doi.org/10.1002/eqe.922.

[33] Jayaram, N., and J.W. Baker. 2010. "Efficient Sampling and Data Reduction Techniques for Probabilistic Seismic Lifeline Risk Assessment." *Earthquake Engineering and Structural Dynamics* 39:1109–1131. https://doi.org/10.1002/eqe.988.

[34] Anelli, A., F. Mori, and M. Vona. 2020. "Fragility Curves of the Urban Road Network Based on the Debris Distributions of Interfering Buildings." *Applied Sciences* 10(4):1289. https://doi.org/10.3390/app10041289.

[35] Lupoi, G., P. Franchin, A. Lupoi, and P. Pinto. 2006. "Seismic Fragility Analysis of Structural Systems." *Journal of Engineering Mechanics* 132:385–395. https://doi.org/10.1061/(ASCE)0733-9399(2006)132:4(385).

[36] Ghosh, J., and J.E. Padgett. 2010. "Aging Considerations in the Development of Time-Dependent Seismic Fragility Curves." *Journal of Structural Engineering* 136:1497–1511.

BOX 4-2
What Is a Numerical Simulation?

Numerical simulations enable computer-based testing of a complex system under a range of input factors that replicate aspects of the real world to produce a range of output predictions that show designers and decision makers how that system may perform under many different conditions. Therefore, they facilitate testing the performance of systems under a wide variety of circumstances—for example, hazards—to understand the range of possible performance outcomes (functionalities) given that the hazard occurrence and intensity are highly uncertain.

For example, a simulation model might assess the damage suffered by a bridge under a range of flood conditions, varying the assumptions on the strength of key components such as foundations, erosion protection, and structural strength.

curves relate the intensity measure of an event at one location (e.g., the peak ground acceleration of an earthquake or the water depth in a storm surge) with the expected level of damage for a component or system. Fragility curves are an explicitly probabilistic tool, whereas vulnerability curves hide the uncertainties and present mean values of damage. Uncertainties in implementing the recovery plan (e.g., duration of the various recovery tasks or resource availability) can also be captured through analytical models or numerical simulation (see Box 4-2).[37,38,39]

Each realization or sample of an extreme event scenario, a damage scenario, a recovery plan scenario, and a specific implementation scenario results in a different sample of functionality recovery curve. If the analysis is repeated for different samples, it is possible to obtain a set of recovery curves for the system. In Figure 4-8, the set of scenarios contains four sample functionality recovery curves marked in purple, yellow, green, and blue.

A direct approach to building probabilistic resilience metrics is to compute the statistics of the deterministic resilience metrics (discussed in the previous section of this chapter) assessed for each sample functionality recovery curve. For instance, it is possible to compute the mean, standard

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[37] Decò, A., P. Bocchini, and D.M. Frangopol. 2013. "A Probabilistic Approach for the Prediction of Seismic Resilience of Bridges." *Earthquake Engineering and Structural Dynamics* 42(10):1469–1487. https://doi.org/10.1002/eqe.2282.

[38] Karamlou, A., and P. Bocchini. 2017. "Functionality-Fragility Surfaces." *Earthquake Engineering and Structural Dynamics* 46:1687–1709. https://doi.org/10.1002/eqe.2878.

[39] Sun, W., P. Bocchini, and B.D. Davison. 2020. "Model for Estimating the Impact of Interdependencies on System Recovery." *Journal of Infrastructure Systems* 26:04020031. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000569.

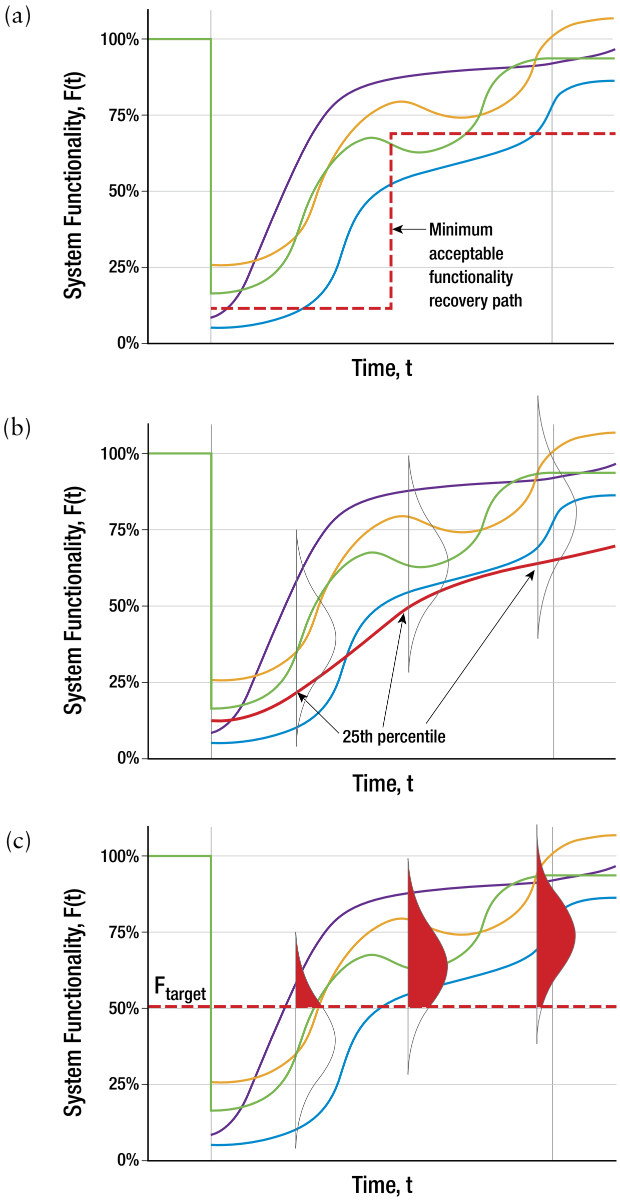

FIGURE 4-8 Examples of probabilistic resilience metrics based on the functionality recovery curve. The gray curves in (b) and (c) represent distributions of all of the functionalities in the simulation scenarios at the selected point in time.[40]

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[40] Used with permission from Paolo Bocchini.

deviation, and quartiles of the resilience index. The same applies to the time to complete recovery, the time to reach a target level of functionality, the minimum functionality, and the other deterministic resilience measures.

The probability of observing an unsatisfactory recovery curve has direct applications in evaluating resilience probabilistically. For example, a railroad company may decide that at no time, even after extreme events, should their capacity drop below 20% (which may correspond to the ability to transport highly perishable items), and that 2 weeks after a disruptive earthquake their functionality should be at least back to 70%. These constraints define a "minimum acceptable functionality recovery path" (dashed line in Figure 4-8a). The percentage of the recovery curves that at any time dip below the minimum acceptable functionality recovery path is a probabilistic metric of failing to achieve the target. Conversely, the probabilistic metric of resilience is the percentage of sample recovery curves that are always above the minimum path. In Figure 4-8 only the yellow curve is always above the red dashed curve, so in this case, if the four curves are equally likely, the probability of resilience metric would be 25%. In actual assessments, simulations of thousands or millions of recovery curves are used.

A probabilistic metric that results from calculating the distribution of the functionality at each point in time can be used to focus attention on the worst performing cases. In Figure 4-8b, the red curve is made up of the 25th percentile of functionality at each point in time. Once created, this recovery curve—made up of functionality from a range of curves—can be analyzed like any other recovery curve.

The metric represented in Figure 4-8c uses the probabilistic distribution of functionality to create a probabilistic recovery curve for a target level of functionality. For a specified target level of functionality, the probability of having a functionality level equal to or larger than the target is computed for each point in time. As represented in Figure 4-8c, for the target level of 50%, the red areas are the percentage of recovery samples equal to or above 50% functionality at that point in time. Plotting these percentages (or probabilities) over time builds the probabilistic recovery curve for the target functionality.[41]

Other probabilistic metrics can be built in similar ways, starting from the recovery curve samples and focusing on the statistics that are most relevant for the problem at hand. Expanding on this, a multi-hazard approach that protects against multiple probable disaster scenarios can be taken as well (see Box 4-3). Because the condition of an asset (e.g., due to sufficient/lack of maintenance) can affect both its and the system's performance after

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[41] Karamlou, A., and P. Bocchini. 2017. "Functionality-Fragility Surfaces." *Earthquake Engineering and Structural Dynamics* 46:1687–1709. https://doi.org/10.1002/eqe.2878.

BOX 4-3
Multi-Hazard Approach

A multi-hazard analysis approach is essential if the best action to improve resilience to one hazard type may make the system less resilient to other possible hazards.[a] Consider, for example, a resilience enhancing action of locating power switches for generators in a secure, low-lying location. Given this decision, the facility might be more resilient to a human-made attack but could be more likely to fail under a flooding event.

In fact, a resilience measure is a function of the scenario(s) considered in the analysis. A system may be highly resilient under one scenario and much less so under another.

A multi-hazard approach can be exercised using a performance metric (of relevance to the studied system) that normalizes to the system's routine conditions. A multi-hazard approach can be taken through expectation or other strategic operator, such as maximizing worst-case performance.[b] In many cases, this may require a multi-stage stochastic modeling conceptualization where stages correspond with periods of the disaster cycle.

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[a] Argyroudis, S.A., S.A. Mitoulis, M.G. Winter, and A.M. Kaynia. 2019. "Fragility of Transport Assets Exposed to Multiple Hazards: State-of-the-Art Review Toward Infrastructural Resilience." *Reliability Engineering & System Safety* 191:106567. https://doi.org/10.1016/j.ress.2019.106567.

[b] Nair, R., H. Avetisyan, and E. Miller-Hooks. 2010. "Resilience of Ports, Terminals and Other Intermodal Components." *Transportation Research Record* 2166:54–65; Chen, L., and E. Miller-Hooks. 2012. "Resilience: An Indicator of Recovery Capability in Intermodal Freight Transport." *Transportation Science* 46:109–123; Miller-Hooks, E., X. Zhang, and R. Faturechi. 2012. "Measuring and Maximizing Resilience of Freight Transportation Networks." *Computers and Operations Research* 39(7):1633–1643.

a disruptive event, a probabilistic analysis can account for the effects of asset conditions at the time of the disruptive event.

Probabilistic analysis is particularly important because it allows for incorporating the crucial effects of climate change in the resilience assessment. Climate change has important impacts on three aspects of resilience assessment. First, it affects the frequency and severity of weather-related events, which can be reflected in the selection of representative scenarios for resilience analysis. The current practice tends to select scenarios based on past occurrences, but given the dynamism of climate change, scenarios for hazards affected by climate change should be selected based on their predicted frequency and severity in the future.

Second, climate change affects the deterioration process of the infrastructure, by changing the mean environmental conditions (e.g., temperature, humidity, salinity of the air) as well as the magnitude of their fluctuations. This, in turn, affects the fragility curves discussed earlier in the chapter.

Third, climate change affects the context in which extreme events occur. For instance, sea level rise, because it can lead to changes to the subsurface and groundwater tables, may impact the ability to access specific locations and hinder proper emergency response. Moreover, different environmental conditions will affect the speed and effectiveness of the emergency response crews. Extreme temperatures will affect power demand, exacerbating potential interdependencies among power, transportation, and other systems in the wake of a disaster. All of these aspects can be reflected in appropriate recovery models.

The metrics discussed in this chapter can account for these three effects of climate change through proper scenario selection that accounts for future trends, advanced fragility curves that factor in accelerated deterioration, and comprehensive recovery models that account for the future climate. However, integrating climate change into resilience assessment requires combining resilience modeling with climate modeling, which increases the uncertainty in the results. Although the concept of resilience is typically defined around a short but impactful perturbing event, resilience is also affected by the slow but equally important perturbation that climate change can impose on infrastructure assets and transportation systems.

FUNCTIONALITY METRICS FOR TRANSPORTATION SYSTEMS

The deterministic and probabilistic metrics discussed in the previous sections require that the analyst defines and assesses the performance of a transportation asset or system using one or more functionality metrics. Functionality metrics are also critical in measuring the consequences of hazard events and the benefits of resilience interventions, as discussed in Chapter 5. As mentioned, functionality metrics are typically specific to the mode or service and the scale of the analysis.

In engineering, transportation networks are often described using theories and various algorithms that find the best routes and distribute traffic to them. These same theories and algorithms can also be used to analyze the loss of functionality associated with asset damage and travel disruption.[42,43] The appropriate functionality metric for assessing resil-

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[42] Bocchini, P., and D.M. Frangopol. 2011. "A Stochastic Computational Framework for the Joint Transportation Network Fragility Analysis and Traffic Flow Distribution Under Extreme Events." *Probabilistic Engineering Mechanics* 26:182–193.

[43] Bocchini, P., and D.M. Frangopol. 2012. "Optimal Resilience- and Cost-Based Post-Disaster Intervention Prioritization for Bridges Along a Highway Segment." *Journal of Bridge Engineering* 17:1–13.

ience should be related to the performance and services most relevant to the mission of the transportation agency. Moreover, functionality might be computed based on stakeholder perspectives and from either the engineering or user level.[44,45] Typically, these functionality metrics relate to business continuity. Some examples used for resilience analysis include throughput of cargo via rail[46] or maritime systems;[47] takeoffs and landings at airports;[48] berths on arrival,[49] throughput,[50] and minimum throughput[51] at ports; travel time or delay on roadways;[52,53] and service levels in transit.[54,55]

While an exhaustive list of these metrics is beyond the scope of this report and can be found in scientific papers, some illustrative examples of these metrics follow.[56]

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[44] Asadabadi, A., and E. Miller-Hooks. 2018. "Co-opetition in Enhancing Global Port Network Resiliency: A Multi-Leader, Common-Follower Game Theoretic Approach." *Transportation Research Part B* 108:281–298.

[45] Vodopivec, N., and E. Miller-Hooks. 2019. "Transit System Resilience: Quantifying the Impacts of Disruptions on Diverse Populations." *Reliability Engineering & Systems Safety* 191(11):106561.

[46] Chen, L., and E. Miller-Hooks. 2012. "Resilience: An Indicator of Recovery Capability in Intermodal Freight Transport." *Transportation Science* 46:109–123.

[47] Asadabadi, A., and E. Miller-Hooks. 2018. "Co-opetition in Enhancing Global Port Network Resiliency: A Multi-Leader, Common-Follower Game Theoretic Approach." *Transportation Research Part B* 108:281–298.

[48] Faturechi, R., and E. Miller-Hooks. 2014. "Travel Time Resilience of Roadway Networks Under Disaster." *Transportation Research Part B* 70:47–64.

[49] Zhou, C., J. Xu, E. Miller-Hooks, W. Zhou, C. Chen, L. Lee, E. Chew, and H. Li. 2021. "Analytics with Digital-Twinning: A Decision Support System for Maintaining a Resilient Port." *Decision Support Systems* 143. https://doi.org/10.1016/j.dss.2021.113496.

[50] Nair, R., H. Avetisyan, and E. Miller-Hooks. 2010. "Resilience of Ports, Terminals and Other Intermodal Components." *Transportation Research Record* 2166:54–65.

[51] Asadabadi, A., and E. Miller-Hooks. 2020. "Maritime Port Network Resiliency and Reliability Through Co-opetition." *Transportation Research Part E* 137:101916.

[52] Faturechi, R., and E. Miller-Hooks. 2014. "Travel Time Resilience of Roadway Networks Under Disaster." *Transportation Research Part B* 70:47–64.

[53] Fotouhi, H., S. Moryadee, and E. Miller-Hooks. 2017. "Quantifying the Resilience of an Urban Traffic Signal-Power Coupled System." *Reliability Engineering & Systems Safety* 163:79–94.

[54] Vodopivec, N., and E. Miller-Hooks. 2019. "Transit System Resilience: Quantifying the Impacts of Disruptions on Diverse Populations." *Reliability Engineering & Systems Safety* 191(11):106561.

[55] Chan, R., and J. Schofer. 2015. "Measuring Transportation System Resilience: Response of Rail Transit to Weather Disruptions." *Natural Hazards Review* 17(1). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000200.

[56] Sun, W., P. Bocchini, and B.D. Davison. 2020. "Resilience Metrics and Measurement Methods for Transportation Infrastructure: The State of the Art." *Sustainable and Resilient Infrastructure* 5:168–199. https://doi.org/10.1080/23789689.2018.1448663.

Weighted Sum of Assets in Service

The functionality metric “weighted sum of assets in service” is especially useful for networks where not all links are equally important. For example, for the resilience tables mentioned in the previous section, if the target is set to “90% of roads open,” it is necessary to specify what “90%” means. Is it 90% of the road capacity or 90% of the road lengths? One way to address this question is to assign a “weight” or “importance factor” to each road segment. A weight could be number of lanes, flow capacity, average daily traffic, traffic flow in peak hours, or some combination of these. The weight of the roads that are open divided by the total weight of the system is a way to assess the percentage of the system that is functional, while also partially accounting for the system topology and traffic capacity.[57]

Total Travel Time

Metrics such as “total travel time” track functionality from the perspective of the ability of the transportation network to handle flows of vehicles, passengers, or goods. These metrics still need to be defined in terms specific to the analysis. For example, the functionality metric total travel time of trips originating during the peak hour of weekday travel in a city measures the effects of the hazard when the highway network is already congested.[58] Changes in total travel time capture the effects of damage and disruptions and the resulting congestion that may occur even on highway segments that are not directly damaged by the extreme event. If a bridge is closed because of an earthquake, part of the traffic that was supposed to cross the bridge will be rerouted to other portions of the highway network and to secondary routes. Detours and delays from additional congestion increase travel time.[59]

Connectivity

Connectivity metrics capture the ability to reach every node from every other node in a network. The degree of connectivity can be measured by

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[57] Karamlou, A., P. Bocchini, and V. Christou. 2016. “Metrics and Algorithm for Optimal Retrofit Strategy of Resilient Transportation Networks.” In *Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks* (T.N. Bittencourt, D.M. Frangopol, and A. Beck, eds.). London: Taylor & Francis Group, pp. 1121–1128.

[58] Bocchini, P., and D.M. Frangopol. 2011. “A Stochastic Computational Framework for the Joint Transportation Network Fragility Analysis and Traffic Flow Distribution Under Extreme Events.” *Probabilistic Engineering Mechanics* 26:182–193.

[59] Bocchini, P., and D.M. Frangopol. 2012. “Optimal Resilience- and Cost-Based Post-Disaster Intervention Prioritization for Bridges Along a Highway Segment.” *Journal of Bridge Engineering* 17:117–129. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000201.

the percentage of connected node pairs. More elaborate approaches weight each origin–destination pair by the corresponding volume of trips.[60] Average added distance between locations above the pre-disruption value can also serve as a measure of connectivity.[61]

Metrics for Interdependent Systems or Facilities

In infrastructure, the functionality of one system often affects the functionality of other systems. Power lines and water infrastructure may be located in the rights-of-way for road and rail networks, while many transportation services depend on electric, water, and communications services generated by outside vendors. For instance, the operation, safety, and security of transportation systems are dependent on communications networks that support control, monitoring, data storage, and safety and security functions. These communication services are commonly purchased from vendors (such as telecom and cloud service providers) that own and maintain such networks. Access to transportation connecting a labor force to employment centers in high-density urban centers is also critical for other industries, such as health care and retail. Therefore, to assess the resilience of one system, it becomes necessary to account for the functionality of other interdependent systems.

The buildings that house and facilitate the operation of all transportation systems are a special case of systems, the functionality of which is interdependent. The functionality of buildings—airport terminals, train stations, port operation centers, etc.—is vulnerable to disruptions caused by structural and non-structural damage, loss of critical services such as electricity, or impeded access. Therefore, the vulnerability of the supporting buildings should be assessed and described in relation to their potential for disrupting operations, and functionality metrics should be chosen that directly or indirectly relate to post-event recovery.[62] Tools and methods for the assessment of post-earthquake building functionality and recovery are currently being used in practice.[63,64] For other hazards such as hurricanes,

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[60] Bocchini, P., and D.M. Frangopol. 2013. "Connectivity-Based Optimal Scheduling for Maintenance of Bridge Networks." *Journal of Engineering Mechanics* 139:760–769. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000271.

[61] Zhang, X., E. Miller-Hooks, and K. Denny. 2015. "Assessing the Role of Network Topology in Resilience of Transportation Systems." *Journal of Transport Geography* 46:35–45.

[62] Burton, H.V., G. Deierlein, D. Lallemant, and T. Lin. 2016. "Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience." *Journal of Structural Engineering* 142(8):C4015007.

[63] FEMA (Federal Emergency Management Agency). 2012. *Seismic Performance Assessment of Buildings*. FEMA P58 Report, Applied Technology Council.

[64] Almufti, I., and M. Wilford. 2013. *REDi™: Resilience-Based Earthquake Design (REDi) Rating System*. London: Arup Group.

tornadoes, flooding, and fire, methods for assessing post-event building functionality are still in the research stage.[65]

METHODS AND TOOLS FOR ANALYZING HAZARD MITIGATION

To improve resilience, transportation agencies need methods to analyze investments designed to prevent damage and disruption and speed recovery. Off-the-shelf and ad hoc software tools developed for a specific purpose can assist investment analysis.

Investment Decision-Making Process

The focus of research on resilience analysis has been on characterizing the processes of disruption, response, and recovery, that is, given a disruption, how does the system perform? For resilience analysis to be useful for analyzing investments designed to prevent loss, the chosen models and metrics must be sensitive to the proposed investment. For example, to analyze a proposed structural retrofit for a bridge, a model that uses fragility curves[66] must be able to predict the changes in the associated fragility curve resulting from the retrofit. If the model could reflect the change in the fragility curve resulting from the preventive action, then the impact of the proposed action on resilience could be assessed by running the model twice, with and without the preventive action, producing metrics with and without the changes induced by the preventive action. The difference between the two metrics is an estimate of the preventive action's impact on resilience.

While the use of functionality recovery curves to analyze investments in resilience is easy to explain in theory, the transition to practice is only in the beginning stages. There is still much work to be done on developing implementable models and metrics, specifically models that relate in fragility curves to mitigation investments. In addition, the data needs are quite intensive. Agency studies of past disruptions and hazard events are needed that describe, measure, and evaluate the recovery process and characterize resilience. Such studies enable agencies to analyze their own performance, identify weaknesses, and prioritize improvements. Studies are also needed that relate types of infrastructure assets, contexts, and hazard characteristics to general recovery curves, thus enabling predictions of the impacts of asset design and context changes on resilience.

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[65] Abdelhady, A.U., S.M. Spence, and J. McCormick. 2020. "A Framework for the Probabilistic Quantification of the Resilience of Communities to Hurricane Winds." *Journal of Wind Engineering and Industrial Aerodynamics* 206:104376.

[66] Fragility curves display the probability of a component/system to reach a certain low performance threshold for a given level of the intensity measure.

Mitigation Analysis Tools

The Interdependent Networked Community Resilience Modeling Environment (IN-CORE)[67] and the Probabilistic Resilience Assessment of Interdependent Systems (PRAISys)[68] are examples of the next generation of community resilience analysis tools. IN-CORE is designed to model the impact of natural hazards and community resilience and recovery. PRAISys is designed to conduct post-event resilience analysis of communities by addressing the interdependencies among infrastructure systems in a probabilistic way. These tools can also effectively capture the resilience outcomes of detailed mitigation actions, preparedness actions, and general operational changes (e.g., changes in the disaster response policies, investments in equipment and personnel for emergency response, and coordination of mutual aid agreements). The tools can be used to conduct specific analyses to assess many of the functionality metrics described in this chapter. However, the analyst has to perform a preliminary data collection from sources external to the tools before conducting any analyses. Because of the complexity of the associated data collection and, to some extent, the software programs, their application is warranted only when other approaches are deemed insufficient and the magnitude of the investment justifies a thorough resilience analysis.

Sufficient data availability is also a challenge for the private and proprietary resilience software tools developed over the past decade. These tools rely on artificial intelligence (AI) and data-driven approaches to bypass the engineering modeling efforts that more well-established analysis approaches have built over time. These AI approaches, however, require vast amounts of data to train the AI models; by definition, data on extreme natural hazards and their effects are scarce.

CHAPTER SUMMARY

The research literature on measuring resilience with functionality recovery curves and their associated metrics, as presented in this chapter, is currently useful for helping transportation agencies conceptualize the performance of their assets and systems during and after a natural hazard event and to communicate resilience concepts with stakeholders. Research into functionality recovery curves also emphasizes the importance of robust fragility curves and functionality metrics, both of which are useful and sometimes necessary for the types of resilience analysis that would be conducted as part of

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[67] Center of Excellence for Risk-Based Community Resilience Planning. 2018. *IN-CORE Manual 1.0.0.* https://incore.ncsa.illinois.edu/doc/incore.

[68] Bocchini, P., B.D. Davison, A.-M. Esnard, A.J. Lamadrid, D. Mitsova, A. Sapat, R. Sause, L.V. Snyder, and W. Sun. 2020. "The PRAISys Platform." www.praisys.org.

the framework presented in Chapter 5. Table 4-2 summarizes functionality metrics for a variety of modes and services. This summary is based on the committee's review of metrics used in resilience research and practice.

TABLE 4-2 Functionality Metrics in Use in Resilience Research and Practice[69]

All Modes and Some Facilities	
System level/facilities	Capacity, delay (travel time), safety
Roadways	
System level	Connectivity, lengths of network links
Pavement	Serviceability
Facilities/information technology (IT)/ communication systems	Up/down, downtime
Regional Passenger Rail	
Signal systems/power/IT/communication systems/maintenance facilities	Up/down, downtime
Power	Fraction with/without power
Stations	Open/closed
Bus; Heavy, Light, and Commuter Rail; Last-Mile Transit	
System level	On-time performance, number of transfers
Track	Serviceability
Signal systems/power/IT/communication systems/maintenance facilities	Up/down, downtime
Stations	Open/closed
Freight Rail	
Track	Serviceability
Signal systems/power/IT/communication systems/maintenance facilities	Up/down, downtime
Terminals	Open/closed, service time
Intermodal Transit Terminals	
Node level	Connectivity, number of modes operating
Terminal	Open/closed, throughput
Power/IT/communications systems	Up/down, downtime
Power	Fraction with/without power

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[69] From the committee's review of metrics used in resilience research and practice.

Walking/Bicycling/Rolling	
Special-purpose lanes/trails	Open/closed
Sidewalks	Accessibility
Parking/shared mobility infrastructure	Accessibility
Air Transportation	
System level	Connectivity, number of transfers, take-offs/landings, throughput, number of travelers served
Terminal/control tower/taxiway/apron/ramps/aircraft stands/facilities (maintenance)/freight/parking/hangars	Up/down, downtime
Runways	Open/closed, downtime, number of take-offs/landings, on-time performance
Fuel systems	Availability
IT/lighting/communications systems	Up/down
Waterways	
System level	Connectivity, speed
Docks/ports	Open/closed
Links	Speed
Locks	Throughout capacity, open, closed
Pipelines	
System level	Flow rate
Storage facilities	Capacity, open, closed
Surface-Aviation-Water Intermodal Terminals	
Facility	Berth/to gate on arrival, open/closed, throughput, service times
Power/IT/communication systems/maintenance facilities	Up/down, downtime
Operators	Throughput, service time, berth on arrival

However, to use the concept of recovery curves for making investment decisions (i.e., in an *a priori* context), agencies would need to estimate, quantitatively, the curve before and after an investment in the face of a disruption. While the curves can be measured *ex post* for a specific, experienced disruption, there are currently no operational tools to estimate them after an investment in resilience has been made. In part, this is because the future recovery curve depends not only on the design of the system but also on the effectiveness of the investment in mitigation actions, the specific characteristics of the disruption, and the response and restoration resources deployed after a future disruption. Recovery curves also presume a perturbing or hazard event and thus require additional work to adapt them to the gradual, chronic, and likely permanent changes associated with climate change.

Significant work still needs to be done on developing functionality metrics for transportation and incorporating case study data that chart hazard recovery over time. Research is also needed to develop practical ways to predict changes in functionality recovery curves brought about by specific mitigation measures to support investment to prevent future disruptions. While research is creating mitigation analysis tools that go beyond the high-level resilience investment analysis possible with the Federal Emergency Management Agency's Hazus-MH (described in Chapter 3), these new tools still require significant amounts of data that may not be accessible to transportation agencies today.

5

Decision Support Framework

Researchers have sought to develop direct measures of transportation system resilience, as discussed in the previous chapter. Recovery curves, which are conceptualized in the literature, define and describe resilience in terms of the loss of functionality and the time needed for restoration. Resilience metrics derived from such curves, in theory, would be comparable across transportation modes and systems. However, functionality recovery curves depend on metrics that are specific to the transportation mode or service, and data needs can be extensive. More studies of past hazard events and transportation system disruptions are also needed for these concepts to be refined for practical application.

Informed by this study's reviews of both academic research on resilience and practitioners' efforts to measure resilience, the committee is not optimistic about the prospect of developing a single metric or small set of metrics to support resilience investment choices, at least in the near term. Indeed, the committee concurs with the finding of a 2019 RAND study that "there is no single metric or value that can perfectly reflect all aspects of resilience in all elements of a given system. Instead, decision makers must look at a variety of metrics to assess and understand the impacts of the investments they make … to improve the resilience of the assets in the transportation system."[1] This finding is not surprising. The variations in

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[1] RAND. 2019. *Incorporating Resilience into Transportation Planning and Assessment.* Report for National Cooperative Highway Research Program project 08-36, Task 146, p. 29. https://www.rand.org/content/dam/rand/pubs/research_reports/RR3000/RR3038/RAND_RR3038.pdf.

natural hazards today and over time, geographic settings, and infrastructure characteristics are vast and better measured by a portfolio of metrics.

Interest in developing a salient set of metrics is understandable. Investing in resilience can be risky and requires careful consideration because it entails spending and other costs incurred in the present to gain benefits that may or may not be realized in the future. These decisions need to be well reasoned and based on sound analytic principles and processes that help guide prioritization of assets warranting resilience strengthening and inform the choice of specific investments for this purpose. For such decision support analysis, there is indeed a need for a portfolio of metrics.

The stakes can be high when investments in transportation resilience are neglected or not made in a deliberate and systematic way. By way of example, the Economics Unit of The Port Authority of New York and New Jersey analyzed the economic costs of hazards to the New York metropolitan region.[2] The analysis simulated shutdowns of its airports, seaport, tunnels, and mass transit. Even a 1-day shutdown had significant costs, which increased nonlinearly over 3, 7, and 30 days. Table 5-1 shows the estimates of economic costs for the various time periods and different transportation modes operated by the Port Authority. For the airports, the cost estimates aggregated the costs of trip delay for outgoing and incoming passengers as

TABLE 5-1 Economic Costs Associated with Disruptions to New York and New Jersey Port Authority Transportation Facilities (in millions of 2018 dollars)[3]

	Days Shut Down			
	1	**3**	**7**	**30**
Airports	**$178.7**	**$775.5**	**$1,414.8**	**$4,048.4**
Newark	*$62.6*	*$251.9*	*$460.2*	*$1,301.3*
JFK	*$75.9*	*$343.3*	*$658.0*	*$1,871.4*
LaGuardia	*$40.2*	*$180.3*	*$296.6*	*$875.7*
Seaport Facilities	**$22.2**	**$202.7**	**$535.1**	**$2,038.6**
Trans-Hudson Tunnels	**$19.1**	**$56.7**	**$129.9**	**$549.2**
PATH	**$2.4**	**$5.4**	**$17.4**	**$80.4**

NOTES: Figures may not total due to rounding. Cost estimates should not be added together as estimates were calculated for each mode in isolation. PATH = Port Authority Trans-Hudson.

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[2] Eshleman, C. 2018. "A Multi-Criteria Decision Index Employing Single-Criterion Features for Evaluation of Transport Infrastructure." TRB Annual Meeting.

[3] The Port Authority of New York and New Jersey, Regional Economic Analysis. 2018. "The Consequences of Facility Shutdowns."

well as the disruptions to business activity that may result from the cancellation of travel altogether. The costs of disruption for seaport facilities were made up largely of the additional inventory costs of extending the supply chains and accommodating delays in bringing goods to market. For mass transit (Port Authority Trans-Hudson) and travel through the tunnels, the evaluation accounted for travel time increases and potential productivity losses as a result of remote work.

While the Port Authority's analysis focused on a select set of measurable economic costs, more complete analyses would also likely have revealed other societal costs such as lost lives, the consequences of injuries, and environmental damages, as well as repair costs for infrastructure and other unmeasured costs resulting from delayed and missed person-trips and freight movements.

In this chapter, consideration is given to the structure and elements of a decision support process, or framework, that practitioners like the Port Authority can use to make well-considered investments in the resilience of their transportation infrastructure. Some of the elements, or steps in the process, are informed by research but are derived largely from existing practice, founded on previous efforts by the federal modal administrations, other federal agencies, state and local transportation agencies, and private industry.

Before turning to the framework idea, the next section of the chapter identifies some general principles that the committee believes should underpin such an effort. The key steps in the framework are then discussed. These steps focus primarily on assessments of resilience benefits. In other words, they are intended to identify and quantify to the extent possible the prospective benefits from making specific investments in resilience that will avoid or lessen the societal costs from natural disasters as they impact transportation systems and their critical functionality. The steps lead to societal benefit measures that can be weighed against measures of the cost of making specific investments, including the resources required to make a resilience improvement as well other relevant considerations such as the opportunity cost of not using those resources for other socially valuable purposes. Thus, while the proposed decision support framework itself will not always produce results that are actionable in the sense that they will provide decision makers with an objective list of resilience improvements that should be made, they can be used to inform such decisions as a key part of a societal benefit-cost analysis (BCA).

GENERAL PRINCIPLES OF A DECISION SUPPORT FRAMEWORK

The committee believes that a decision support framework should have certain qualities that will ensure that it is generally applicable and sufficiently practical to use. In particular, the framework should be

- Comprehensive so that it can be applied across modes, locations, time, and hazard types;
- Capable of accounting for uncertainties about the future;
- Practical to use, requiring data that are reasonable to obtain, and involving analyses that can be readily linked to more informed decision making;
- Objective in the sense that quantitative metrics are used where available and reasonable, and qualitative assessments are informed by data or expert judgment and are transparent;
- Broadly based by taking into account a locale's or region's quality of life and economy in addition to accounting for direct (and often more readily measurable) impacts on infrastructure owners and users;
- Attentive to different time dimensions and cognizant of the resilience that is needed for immediate response and recovery from disaster as well as the resilience needed over the longer term for disruptions over the life cycle of assets, such as from the effects of climate change; and
- Informed by the results of past investments, which can be helpful for understanding where resilience investments have paid off.

A MULTI-STEP DECISION SUPPORT FRAMEWORK

The steps that make up the framework for measuring resilience benefits—or the societal costs avoided from adding resilience—and costs are logical and straightforward. Figure 5-1 depicts them. They start with the conduct of an inventory of assets, both existing and planned. Next, perhaps integrated with the asset inventory, is evaluation of the criticality (importance or value) of these assets, particularly with respect to their societal functions. This is followed or accompanied by characterizations of the types and likelihood of hazards that could affect assets in this inventory. In this regard, the framework can be viewed as multi-hazard. Having this information, a transportation agency can then make assessments of the vulnerability to hazards of the most functionally critical assets and characterize the consequences should the vulnerability become exposed in a hazard event.

One can think of this entire process as a means of estimating or characterizing risk, or as tantamount to identifying the prospective benefits and costs of different options to reduce this risk to varying degrees. Decisions about whether to implement these options, with their attendant resilience benefits and the costs associated with their implementation, can then be informed by BCA. More discussion of each step in this process is provided next.

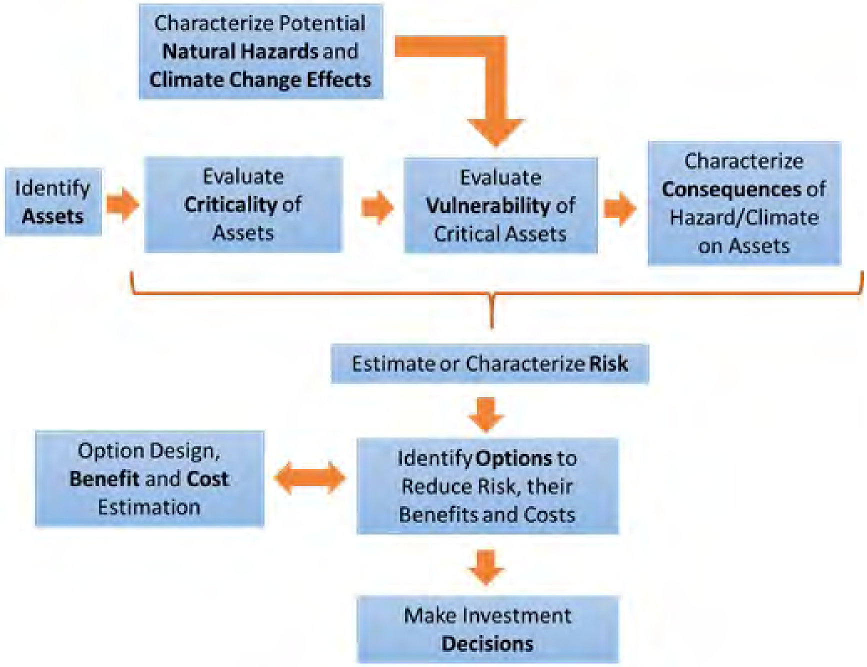

FIGURE 5-1 Components of the proposed decision support framework.

Identifying Assets

Transportation assets refer to the physical infrastructure, transportation workers, and institutional resources for all relevant transportation modes: road, railroad, maritime, inland waterways, aviation, public transit, bicycle and pedestrian facilities, and pipelines.[4]

To conduct resilience analysis, agencies need to have up-to-date information on their assets, including an asset's location, condition, vulnerability to damage, and history. For transportation agencies, asset management is typically an ongoing process that meets a variety of management goals, involves asset inventory data, and may include vulnerability information. The current regulatory framework for some transportation modes requires maintaining active asset management programs. State Departments of Transportation (DOTs) are required to develop asset management plans

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[4] USGCRP (U.S. Global Change Research Program). 2021. "U.S. Climate Resilience Toolkit." https://toolkit.climate.gov/content/glossary.

that are then certified by the Federal Highway Administration (FHWA).[5] Likewise, the Federal Transit Administration (FTA) requires public transit agencies to develop and implement a Transit Asset Management Plan.[6] Depending on the scale of the envisioned resilience investment, a transportation agency might have a system-level inventory as well as a project-specific inventory, with different levels of detail. For example, Washington State DOT has incorporated resilience analysis at a corridor level and thus has not used detailed inventories of individual assets. Box 5-1 presents some examples of inventory elements useful for resilience analyses at the physical asset and system infrastructure levels.

Asset inventories should include information related to an asset's resilience. This information identifies whether (and how) an asset is exposed and vulnerable to natural hazards and the asset's criticality to the operations of the facility. The Port of Long Beach began the development of its Climate Adaptation and Coastal Resiliency Plan with an inventory of critical assets. The inventory included the piers, road and rail transportation, utilities, critical buildings, and the value and type of cargo. Infrastructure outside the port boundaries, such as roads, that are critical to port operations were also included. They then used the asset inventory to analyze which assets were exposed and vulnerable to natural hazards.[7]

In addition to inventories of physical assets, transportation agencies should also keep an inventory of organizational assets specifically designed for operational resilience, such as procedures, tools, and guidance; continuity of operations plans; and staff training resources. Assets should include physical and organizational assets designed to prevent disruption and to speed recovery. Asset inventories need periodic updating to reflect changed assets and asset conditions.

Evaluating the Criticality of Assets

Criticality can be understood as the importance of an asset to the agency's mission and to society. Criticality metrics capture this importance from the perspective of business continuity, users, the local or regional economy, health and safety, equity, and other social factors. As described in Chapter 3, FHWA encourages agencies to conduct a criticality assessment early in the analysis process to prioritize which assets or parts of the network to

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[5] FHWA (Federal Highway Administration). 2019. "How TPM and Asset Management Work Together." https://www.fhwa.dot.gov/tpm/resources/working.cfm.

[6] FTA (Federal Transit Administration). 2016. "National Transit Asset Management System Final Rule." https://www.transit.dot.gov/regulations-and-guidance/asset-management/national-transit-asset-management-system-final-rule.

[7] Port of Long Beach. 2016. *Port of Long Beach Climate Adaptation and Coastal Resiliency Plan.* https://www.slc.ca.gov/wp-content/uploads/2018/10/POLB.pdf.

BOX 5-1
Examples of Asset- and System-Level Inventory Attributes Relevant for Resilience Analysis

Asset Level

- Asset attributes
  - Name and number
  - Location
  - Description (e.g., design)
  - Age
  - Asset class/group
  - Replacement/renewal value
  - Design life or expected remaining life
  - Rehabilitation schedule
- Asset condition
- Functionality—services provided, volumes carried, traffic mix
- Asset history (e.g., prior damages, rehabilitation)
- Inspections, maintenance, and rehabilitation resources (including those to increase resilience, such as storm water management improvements, grade improvements, etc.)

System Level

- Number of inspections and maintenance activities on schedule
- Upgrades that have increased resilience (e.g., by raising the facility's elevation or boosting earthquake resistance)
- Capacity (i.e., volumes and loads)
- Utilization (i.e., volumes and types of traffic loads carried)
- Critical intermodal connections
- Redundancy
- Interoperability and interdependence with other systems (including connecting elements)

evaluate for vulnerability. Criticality metrics are typically a composite of several measures, not all of which may be represented in monetary terms. Any process used to score or weight the component parts of criticality metrics should be transparent.[8]

The Colorado DOT (see Chapter 3) developed criticality metrics for the overall highway system that combined physical inventory metrics with indicators of economic and social value. The Hillsborough County

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[8] U.S. DOT (U.S. Department of Transportation). 2014. Assessing Criticality in Transportation Adaptation Planning. https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/criticality_guidance/criticality_guidance.pdf.

BOX 5-2
Examples of Factors to Consider for Assessing Criticality

- Level of current use (e.g., traffic volume and mix)
- Projected future traffic volume
- Projected population density
- Projected employment density
- Projected freight traffic (e.g., volumes, key product types)
- Proximity or primary route to major economic and community centers
- Part of strategic transportation network (e.g., National Highway Freight Network or Strategic Highway Network; hub airports with higher share of connecting flights)
- Intermodal connections
- Evacuation route
- Link to first response facilities
- Transit coverage and ridership
- Social and demographic attributes of communities served (e.g., the Centers for Disease Control and Prevention's Social Vulnerability Index)
- Characteristics of redundant routes and modes (e.g., availability, added distance and time, traffic volume and load-bearing capacity)

Metropolitan Planning Organization, in its FHWA resilience pilot,[9] used its travel demand model to assess criticality based on the regional significance of roads in the county. The analysis calculated an area-based criticality metric made up of the population and employment density of every Traffic Analysis Zone (TAZ). For the Origin-Destination (O-D) criticality measure, the TAZ criticality ratings were used to calculate a criticality score for each O-D pair, which was transformed into the criticality of traffic flows on the road network. Finally, the road network was sorted into three criticality tiers.

Box 5-2 presents some examples of the factors to consider when assessing criticality, both quantitatively and qualitatively. In the absence of data, stakeholder opinions are often used to score criticality.

Asset criticality can be assessed as part of the asset inventory or as a separate step. Criticality metrics can even be imported from other planning processes. As described in Chapter 3, when criticality metrics are combined with metrics for vulnerability or risk, they can also give an indication of overall resilience at the system or agency level.

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[9] Hillsborough County Metropolitan Planning Organization and Planning Commission. 2014. *Hillsborough County MPO: Vulnerability Assessment and Adaptation Pilot Project.* https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/florida/final_report/florida.pdf.

Characterizing Natural Hazards and Their Likelihood

Evaluation and quantification of the character and likelihood of natural hazards with the potential to affect the transportation system under analysis is a key element of the decision support framework. Hazard characterization is an input to the main resilience investment analysis and typically uses externally provided data. Implementing this step of the framework may involve defining a criterion event (e.g., 200-year storm—annual probability of 0.5%) or set of events and requires accounting for changes in environmental conditions due to climate change. As discussed in Chapter 3, criterion events reflect the level or intensity of the hazard chosen as the standard for design and evaluation, relevant to the specific transportation system and assets under evaluation. The criterion event or environmental conditions will differ by location and asset type. The types of natural hazards and their potential to damage infrastructure assets and disrupt travel are covered extensively in Chapter 2. To address uncertainty, a set of criterion events might be defined and used as scenarios in resilience analysis. For example, in some settings it may be appropriate to define and test separate scenarios for riverine flooding, wildfires, and extreme snowfall.

Key aspects for characterizing the natural hazard are the type of hazard and its location, scale, intensity, frequency, persistence (such as sea level rise), duration, and the timing of any advance warning. The likelihood or probability of an event has traditionally been determined from the historic frequency of events. As discussed above, uncertainties can be addressed by considering a range of events or scenarios.

However, climate change causes the analysis of likelihood based on historic data to be inaccurate. The likelihood and character of natural hazards are changing, and forecasts need regular updates using trend analysis with recent data and using scenario modeling, which tests the consequences of a range of future conditions. The uncertainty around the effects of climate change is compounded when using longer analysis horizons, typical of infrastructure investments with long life cycles. This suggests that if changes in natural hazard risks accelerate, a reexamination of resilience investments may be warranted before the end of asset life is reached. In the face of climate change, regular adaptation is likely to be a safer strategy than "set-it-and-forget-it."

Transportation agencies should obtain and maintain an up-to-date inventory of data describing the specific natural hazards affecting their transportation assets. These agencies depend on other federal and state agencies and private organizations for much of the information, including trends and forecasts about natural hazards and climate change effects (e.g., the National Oceanic and Atmospheric Administration's Atlas 14 precipitation data,[10] the Federal Emergency Management Agency's flood maps,[11] FHWA's Climate Model Intercomparison Project Climate Data Processing Tool,[12] the Colorado Geological Service,[13] OpenQuake[14]). It is essential that these significant data be updated and maintained. As discussed in Chapter 2, transportation agencies must augment the external data with local and transportation agency experience. Some of the natural hazard data that transportation organizations should consider in their analysis are identified in Box 5-3.

Because many areas of the country are prone to multiple hazards, the possibility of multiple, simultaneous hazards must be addressed in the resilience analysis. The analysis should consider the likelihood of several hazard events happening simultaneously or in quick succession and the probability of cascading events, when one event causes or worsens a subsequent event.

Evaluating the Vulnerability of Assets

Vulnerability refers to the susceptibility of assets and systems to damage and disruption. That is, for a given hazard (e.g., a hurricane) of a given magnitude (e.g., Category 3), how much damage to assets and travel disruption will occur? Vulnerability is influenced by the location, design, materials, and other attributes of the asset and by the characteristics of the natural hazard.

While vulnerability assessments for assets focus on the likelihood of failure, damage, or disruption at the specific location of each asset, vulnerability assessments at the system or network level require a different set of metrics or indicators. Examples of system-level metrics are listed in Box 5-4. Vulnerability assessment should also include assessments of interdependent systems (e.g., an earthquake leading to failure of the power supply needed to run rail transit) and of simultaneous and cascading hazard events.

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[10] NOAA (National Oceanic and Atmospheric Administration). 2017. "NOAA Atlas 14 Point Precipitation Frequency Estimates." https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html.

[11] FEMA (Federal Emergency Management Agency). 2018. "FEMA Flood Map Service Center." https://toolkit.climate.gov/tool/fema-flood-map-service-center.

[12] FHWA. n.d. CMIP Climate Data Processing Tool 2.1. https://fhwaapps.fhwa.dot.gov/cmip.

[13] Colorado Geological Survey. n.d. "Colorado Geological Survey: Geoscience for Colorado." https://coloradogeologicalsurvey.org.

[14] OpenQuake. n.d. "The OpenQuake Platform." https://platform.openquake.org.

BOX 5-3
Examples of Natural Hazards and Climate Change Stressors to Consider (including intensity, duration, geographic extent, and other attributes)

Meteorological Hazards
- Avalanche
- Debris flow
- Drought
- Fire/wildfire
- Flood/flash flood
- Hail
- Heavy rain
- High wind
- Ice flow
- Lightning
- Mudflow
- Snow
- Storm surge
- Tornado
- Tropical cyclone
- Water table changes

Geological Hazards
- Earthquake
- Land subsidence
- Landslide and rockfall
- Sinkhole
- Tsunami
- Volcanic eruption

Climate Change–Related Hazards
- Precipitation: changes in averages, extremes, and seasons
- Temperature: changes in averages, extremes, and seasons
- Sea level rise
- Interaction of precipitation, temperature, and sea level changes with other meteorological hazards
- Freeze-thaw events

Evaluating the Consequences of Hazard Scenarios

Consequences measure the economic and social costs resulting from the relevant hazard. Consequences are the values lost or disrupted. The major categories of consequences are the costs to restore functionality and repair or replace the asset, and the value, including criticality, of the functionality that was disrupted because of the hazard. In the context of climate change,

BOX 5-4
Examples of System-Level Vulnerability Metrics

- Network (route) miles in 100- and 200-year flood zones
- Number of critical facilities in 100- and 200-year flood zones
- Number of bridges within 100-year floodplain
- Coastal railroad route miles less than 2 feet above 2050 projected sea level rise
- Areas of inundation due to sea level rise
- Percentage of critical equipment affected by high/low temperatures
- Number of (or list of) critical components subject to failure due to ambient temperature above X°F
- Miles of highways in high wildfire danger areas (wildfires within 5 miles in past 10 years)
- Annual percentage of routine facility inspections completed on time
- Facility (bridges, highways, airport pavements) condition ratings—number, mileage, or percentages in fair or poor categories
- Number of posted bridges (loads limited below standard) on National Highway System

the costs may be ongoing. Hazard-driven morbidity and mortality to those affected by the hazard are part of the consequences. Examples of metrics for consequences are presented in Box 5-5. The costs of lost functionality will generally depend on the transportation agency's operational resilience—how quickly it can respond and restore service on the infrastructure that is damaged. Other consequences may depend on the agency's mission. For example, the San Diego International Airport includes the consequences to the wildlife habitat that it maintains. Monetizing consequences is necessary to develop risk-based resilience metrics, but it will not always be feasible. The Colorado DOT monetizes the consequences of damage and disruption by computing the annualized owner costs (e.g., asset replacement and cleanup costs) and user costs (e.g., value of time lost to delays and travel costs of detours); it also includes measures of social vulnerability in its criticality analysis process.

BOX 5-5
Examples of Metrics for Consequences

Owner Consequences
- Disruption response costs
- Asset replacement costs
- Asset repair costs
- Cleanup costs
- Loss of revenue
- Liability for injuries or death
- Loss of labor productivity

User Consequences
- Value of time lost to delay
- Cost of added travel for detours and rerouting
- Cost of foregone trips

Community Consequences
- Losses to local and regional economy
  - Business or tourism sales lost
  - Workdays lost
  - Jobs lost
- Environment damage
- Isolation or loss of access
- Other community impacts

Estimating Risk

In the proposed framework, risk is defined conceptually as follows:

Risk = Hazard Likelihood × Vulnerability × Consequences

where

- Risk is the expected value of losses to the economy and society due to the disruption of transportation functionality caused by natural hazards,
- Hazard likelihood describes probabilities of relevant natural hazards,
- Vulnerability measures asset susceptibility to natural hazards, and
- Consequences describe the value of functionality lost because of destruction of assets or service disruptions, including losses to asset owners, asset users, and communities.

Managing the risks resulting from disruptions due to natural hazards and climate change is a key objective for transportation agencies addressing resilience. This requires having an understanding of the risk associated with an asset or parts of the network due to the relevant hazards.

Measuring all of the concepts quantitatively, however, can become difficult or impossible. While for many transportation agencies data availability remains an obstacle to conducting resilience analysis, the complexity of calculating and communicating multi-dimensional relationships is the primary impediment. Because of these complexities, some simplifications might be needed. Some transportation agencies have limited their efforts to evaluating one hazard at a time or to using qualitative scoring to characterize or rank risks, where that scoring is informed by the best data available. As illustrated in Chapter 3 (see Figure 3-1), this qualitative assessment of risk can then be used to prioritize risks in support of resilience investment decisions.

APPLYING THE RESULTS OF THE DECISION FRAMEWORK

By identifying risk, or the expected value of losses to the economy and society due to the disruption of transportation functionality caused by natural hazards, the steps delineated above in essence provide transportation agencies with a quantification of resilience benefits. Those benefits, however, can only be realized in part or in full by making the right investments, and it is likely that decision makers will have multiple resilience investment options to consider. Each option will present costs, which must be weighed against the potential for that option to confer resilience benefits.

Identifying Options to Increase Resilience and Their Benefits and Costs

With an understanding of the risk that natural hazards pose to critical assets or portions of the system, an agency can design candidate mitigation actions and identify and assess their benefits and costs. Increasing resilience through investments can be achieved by a number of actions as described in Chapters 3 and 4, and summarized here:

- Prevent disruption and destruction of transportation facilities and services by
  - Building or rebuilding more robust facilities—for example, by designing new facilities with increased resistance to damage by natural hazards or the impacts of climate change, by protecting bridges against scour, by increasing bridge clearances above waterways, or with seismic retrofits;

  - Adding redundancy—for example, by adding new routes, improving alternative routes, adding or identifying alternative transportation modes, identifying alternative sources of supply of essential resources or services, or acquiring back-up power sources to support critical systems for multiple days (e.g., command and control centers, traffic signals, communication systems, rail crossing barriers, bridge lifts); and
  - Relocating vulnerable facilities away from areas with high hazard exposure (e.g., rivers, coastal zones, unstable rock formations).
- Restore functionality rapidly by
  - Enhancing response resourcefulness—developing disaster recovery plans and securing adequate resources in advance for rapid restoration of functionality, establishing mutual aid or cooperation agreements, creating secure and redundant communications networks and protocols, and/or setting aside emergency funds specifically dedicated for responding to natural hazard/climate change events;
  - Improving quick response capabilities, including implementing event prediction and detection, increasing multi-agency disaster response planning and drilling, preplanning detours and modal diversions, establishing decision processes for rapidly invoking detours and diversions, arranging alternative sources for critical supplies (e.g., food, water, medicines, repair materials), and establishing task order contracts for rescue and rebuilding; and
  - Building or rebuilding infrastructure assets so that they can more quickly recover functionality, including designing bridges and pavements to withstand prolonged immersion in water and installing pumping systems at low-lying airports for quick restoration of operations.

Box 5-6 provides an overview of the types of benefits associated with resilience investments. As with the metrics from previous framework elements (e.g., criticality), while quantification is ideal, it might not always be possible. In those cases, agencies should develop judgmental scales based on qualitative assessments.

Estimating these benefits for a proposed investment is a complex task. With pre- and post-event data, the estimation will be somewhat easier for addressing the benefits of investments for post-disruption restoration and recovery, especially if a good analysis of the impacts of prior events has been conducted. To evaluate projects intended to reduce future disruptions, it is necessary to construct "with" and "without" scenarios (described in Chapter 4) to estimate the costs of disruptions due to a criterion event and

BOX 5-6
Types of Benefits of Resilience Investments

Infrastructure Owner-Operators—Costs Reduced, Avoided
- Emergency operations
- Recovery and restoration
- Reconstruction

Users (freight)—Costs Reduced, Avoided
- Trip delay costs
- Rerouting costs
- Canceled trip costs
- Inventory costs

Users (personal travel)—Costs Reduced, Avoided
- Trip delay costs
- Rerouting costs
- Canceled trip costs
- Trip reliability

Communities—Costs Reduced, Avoided
- Business, tourism sales lost, deferred
- Workdays lost, furloughs, jobs lost
- Injuries and deaths
- Delayed shipment costs (e.g., stockouts, supply chain disruptions)
- Canceled shipment costs (e.g., stockouts, supply chain disruptions)
- Environmental damage costs
- Reductions in damage costs for non-transportation facilities and activities

Communities—Positive Changes
- Jobs gained in restoration, new construction

those costs that would be avoided because of the investment.[15] This requires a detailed understanding of the asset or system being studied, which should come from the asset management plan, as well as a clear specification of the criterion hazard event or events. The difference between "with" and "without" the investment defines the benefit of that investment.

While conceptually straightforward, this process presents several challenges. First, estimating the future damage costs requires good information on the efficacy of the investment. That is why it was suggested that

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[15] Aerts, J.C.J.H., W.J. Wouter Botzen, K. Emanuel, N. Lin, H. de Moel, and E.O. Michel-Kerjan. 2014. "Evaluating Flood Resilience Strategies for Coastal Megacities." *Science* 344:473–475.

focusing on mitigation actions with some proven efficacy is advantageous. Still, design engineers should be able to address changes in structural performance under stress brought about by mitigation actions. Addressing the changes in travel costs calls for the application of travel forecasting tools (as in the Hampton Roads Transportation Planning Organization's use of Volpe's Resilience and Disaster Recovery Metamodel, described in Chapter 3). Capturing the social and economic benefits is important but requires still different tools from the field of economic impact analysis. For more complex cases, some qualitative analysis driven by local data on social characteristics and vulnerability will be essential to address the social and equity impacts of resilience investments.

Integrating these benefits into a single metric also presents a challenge, one that is essentially the same as that faced when making major infrastructure investments. While many of these benefits can be monetized, based on market values, revealed or stated preferences, or other methods, it is likely that some important qualitative benefits will remain and will require judgment.

The evaluation time frame, the future period over which benefits are assessed and aggregated, can be defined based on one of several factors, including the expected or design life of the asset, the period for which a reliable forecast can be made (probably shorter than the design life), or a target year determined by local or national policy. A longer time frame may be more appropriate for addressing the benefits of investments to mitigate the effects of climate change, but evaluating investments over a longer time period increases the uncertainty of the estimates. One way to address this is to plan for the long run but periodically reassess system resilience and consider if mitigating investments need to be adjusted. Selecting flexible, adaptable designs will make it easier to adjust system resilience in the future.[16]

Estimating the costs of options to reduce risk is an essential step in preparing for a BCA. The most obvious costs are the costs to the infrastructure owner of modifying the infrastructure to reduce its vulnerability to damage in the event of a hazardous event. These are both capital (initial) costs and ongoing operation and maintenance costs. But the out-of-pocket cost to modify infrastructure is not the only type of cost that should be considered. If robustness of infrastructure is increased by rebuilding, for example, the infrastructure may need to be taken out of service for a period of time while the reconstruction is under way, reducing or eliminating its ability to provide services to users. If redundancy is increased by building new routes, land for that new construction may need to be acquired by eminent domain from property owners, who may consider the compensation for

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[16] Chan, R., P. Durango-Cohen, and J.L. Schofer. 2016. "Dynamic Learning Process for Selecting Storm Protection Investments." *Transportation Research Record* 2599:1–8.

their property to be inadequate to match their perceived loss. Constructing additional highway capacity may increase highway usage, generating increased emissions of greenhouse gases and other pollutants. Relocating vulnerable facilities to less vulnerable locations may have adverse effects on how well those facilities can serve their customers in normal times. Life-cycle costs are also difficult to estimate.

Benefit-Cost Analysis

Transportation agencies have long used BCA to assess proposed projects; thus, using BCA to analyze resilience improvements adapts a familiar tool to advance resilience. The strengths and the weaknesses of BCA are well known. BCA can incorporate life-cycle—construction, operations, and maintenance—costs for the asset (or operational improvement) and include the life-cycle benefits of resilience to users and society. BCA can also be used to analyze the costs of inaction.

The challenge is to capture all of the costs and benefits necessary to give decision makers a comprehensive picture of proposed resilience improvements. Some categories of benefits, such as equity considerations (which are not always significant), benefits of protecting endangered species, and benefits of preventing low-probability but high-risk events, cannot always be measured quantitatively. Although some aspects of cost estimation, such as life-cycle costs, are not simple tasks, the major challenge in applying BCA is usually getting a comprehensive analysis of benefits. As described, the benefits to be included in the resilience BCA will primarily come in the form of expected reductions in the costs of disruption, including reductions in adverse social impacts and inequitable distributional effects. The National Cooperative Highway Research Program report *Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change—Guidebook* provides up-to-date guidance on integrating resilience into BCA and other investment analysis techniques.[17] Box 5-7 illustrates some of the evaluation measures that might be applied.

Because transportation infrastructure is typically very long-lived, the choice of a discount rate is a critical step in evaluating both the benefits and costs of an infrastructure project. The discount rate converts future benefits and costs to a present value by multiplying the future benefit or cost by $1/(1 + r)^n$, where "r" is the discount rate per year and "n" is the number of years between the decision year and the future year in which the benefit

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[17] NASEM (National Academies of Sciences, Engineering, and Medicine). 2020. *Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change—Guidebook*. Washington, DC: The National Academies Press.

BOX 5-7
Examples of Investment Decision-Making Metrics Derived from BCA

- Benefit-cost ratio
- Return on investment
- Net present value
- Costs avoided
    - Infrastructure damage
    - Incremental transportation costs—time and money
    - Economic disruption costs (due to blocked or delayed flows, late or failed deliveries, product spoilage, etc.)
    - Social disruption costs—social connections, impacts to vulnerable communities, health care, education activities delayed or prevented
- Equity of distributional effects
    - Inequities in the distribution of negative impacts across economic and social groups and on vulnerable populations

or cost occurs. The higher the discount rate, the less those future benefits and costs count in present-value terms.

Guidance from the federal Office of Management and Budget has recommended a real discount rate of 7% since 1992. Over the past 20 years, real rates of return on fixed income assets (such as Treasury bonds) have fallen substantially, calling into question the continuing validity of 7% as an appropriate long-term discount rate. Moreover, a basic element of a discount rate is the rate of time preference, which reflects the rate at which an individual makes trade-offs between future benefits and present benefits. If most individuals will not be alive at the future time, perhaps 50–100 years in the future, when future benefits and costs are realized, then the rate of time preference becomes an intergenerational trade-off. When the benefits and costs are experienced by different generations, it raises questions as to whether an individual's rate of time preference is valid as a measure of how a society should trade off future versus present benefits and costs. As a result, many observers have argued that a lower discount rate, perhaps 3%, is appropriate for discounting future benefits and costs that involve intergenerational trade-offs. Some methodological approaches for BCA have recommended the use of declining discount rates over time to capture the issue of intergenerational equity. For instance, the Green Book used in project appraisals in the United Kingdom recommends an initial discount rate of 3.5% followed by a declining rate schedule for projects with long-term duration.[18]

BCA and the Investment Decision

Formalizing system resilience concepts and analysis into transportation agency decision making can help decision makers make informed choices to manage the risks of disruptions caused by natural hazards and climate change stressors. The results of BCA can be critical to this process, and the framework proposed in this chapter to measure resilience benefits is conducive to the application of BCA. However, BCA is rarely used as the sole basis for decision making. Typically, there are considerations that are omitted from even a good BCA, such as social impacts, equity considerations, and the value to be placed on low-probability but high-risk events. Decision makers in both private and public organizations must make decisions that use judgment to place appropriate weights on these considerations. Nevertheless, a BCA can still be very useful, for example, in distinguishing between options that have different outcomes in terms of measurable costs and benefits but are similar in the more difficult-to-measure considerations.

Given the possibility that some impacts of disruptions due to natural hazards will not be assessed in monetary units, either because doing so is too difficult or uncertain or because the deduced monetary values do not reflect the real value of losses to people, augmentation of classic BCA with additional quantitative measures or qualitative descriptions may be necessary to reflect the full set of benefits in terms of damage costs avoided and costs of resilience investments.

It is possible to conduct BCA not only at the project level but also at the program level. A program-level BCA provides information on what the overall budget of a program should be to achieve certain resilience targets based on BCA principles. No federal tools exist to conduct such analysis for resilience to natural hazards and climate change, but existing models used for condition and performance reporting illustrate the potential for it. For example, FHWA's Highway Economic Requirements System model uses BCA for program-level assessments, in particular to assess the current and future physical conditions and consider standard options for improving pavements. FTA also uses program-level BCA with its Transit Economic Requirements Model that supports its assessment of future capital investment needs.

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[18] HM Treasury. 2020. *The Green Book: Central Government Guidance on Appraisal and Evaluation.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938046/The_Green_Book_2020.pdf.

CHAPTER SUMMARY

This chapter's review of both practice and research suggests that more can be done to make the calculus of resilience a more systematic and deliberate part of transportation asset management and investment decision making. The review suggests that resilience should be measured and assessed using a multi-step, multi-hazard analytic framework. The process of assessing the potential benefits of resilience investments includes detailed inventories of assets (or portions of a network) that exist and are planned; assessments of the characteristics and likelihood of natural hazards occurring in the future; and predictions of the vulnerability of the inventoried assets to disruption, damage, and destruction from the hazards. These assessments should be accompanied by determinations of the criticality, or value, of each asset's functionality and estimations of the consequences of damages to the asset and its lost or degraded functionality. The avoidance of future losses in functionality, as incurred by infrastructure owners and users and the broader community, represents the societal benefits of effective resilience investments.

Investing in resilience requires spending funds in the present to gain benefits that may or may not be realized in the future. The decision to make a resilience investment must consider its prospective benefits in relation to its life-cycle costs, including financial outlays and other sacrifices. BCA is the analytic tool often used to support such decision making. While translating benefits and costs into monetary values facilitates BCA, resilience investments can also be evaluated using quantitative, non-monetary measures and qualitative descriptions to account for the full set of possible outcomes, including equity and distributional impacts. A BCA that yields results showing positive net benefits represents the societal gain from a resilience investment that takes into account its life-cycle costs and benefits. While BCA is rarely used as the sole basis for making decisions that must take into consideration interests such as equity and distributional impacts, a BCA can nevertheless be an important part of the resilience calculus.

6

Conclusions and Recommendations

Disruptions to the functioning of the nation's transportation systems are occurring on a more frequent basis, with increasingly severe consequences, as climate change spawns more extreme weather events, leads to sea level rise, and alters temperature and precipitation norms. Preventing the occurrence and reducing the severity of these disruptions will become increasingly challenging, and the costs to society and the economy will escalate if this challenge goes unmet. There is a compelling case for investing in projects that will make transportation systems more resilient to disruptions by maintaining or quickly regaining their functionality during and after a natural disaster and over time as the climate changes. However, setting priorities and making commitments to investments in resilience can present vexing choices for planners and decision makers. The ability to evaluate the benefits and costs of these investments can support sound choices when resources are limited.

The committee's review of practice and research did not identify a single metric, or even a small set of metrics, that can be readily developed and generally applied to improve the resilience of transportation systems. The analysis of resilience is heavily dependent on metrics for functionality and damage, which differ by mode and infrastructure type. In addition, transportation agencies' vulnerability to natural hazards and climate change effects can vary widely. Agencies also need to be able to be responsive to unique constituent concerns.

Despite these challenges, significant progress has been made over the past decade in integrating resilience criteria into transportation decision making, including the development, piloting, and use of innovative tools for resilience measurement, evaluation, and investment prioritization. The federal modal agencies and the state and local owners of infrastructure have commissioned numerous reports, funded and participated in pilot programs, developed guidance documents, and began implementing the recommended practices. Still, there is much to be done to improve the integration of resilience into the decision making of all transportation agencies, small to large, and across the modes.

The committee concluded that the widespread adoption of a systematic decision support framework is the most promising way for making resilience a key driver of agency decision making. As described in detail in Chapter 5, this decision support framework includes general principles and a multi-step analysis process. The principles are designed to ensure that the framework is practical to use and generally applicable across modes, locations, time spans, and hazards. Resilience decision making should account for uncertainties and be as objective as feasible, preferring quantitative analysis and insisting that qualitative analysis be based on data and expert judgment. Resilience decision making should also be able to analyze strategies that speed response and recovery, as well as those that prevent damage and disruption.

In addition, transportation agencies should be encouraged to take a multi-hazard approach to resilience analysis. Too often, agencies still focus on a repeat of the most recent disaster or focus on only a small set of relevant hazards. Especially because of climate change, agencies should be encouraged to examine the set of plausible hazards. Robust multi-hazard approaches also analyze multiple hazards occurring in quick succession, overlapping hazards, and cascading hazards, when one hazard causes or worsens a subsequent hazard. The gradual impacts of climate change need to be considered as part of multi-hazard assessments, not only because they can be costly on their own but also because they can worsen the impacts of other natural hazards.

The recommended multi-step decision support framework includes detailed inventories of assets that exist and are planned; assessments of the characteristics and likelihood of natural hazards occurring in the future; and predictions of the vulnerability of the inventoried assets to disruption, damage, and destruction from the hazards. These assessments should be accompanied by determinations of the criticality, or importance, of each asset's functionality and estimates of the consequences of damages to the asset and its lost or degraded functionality. Options for improving resilience should be analyzed in terms of their benefits (i.e., loss avoidance and costs, broadly defined).

Benefit-cost analysis (BCA) is the analytic tool often used to support decision making about investment alternatives. BCA offers methods to analyze investments in resilience that require spending funds in the present to gain benefits that may or may not be realized in the future. It can also accommodate the consideration of life-cycle costs. However, while evaluating the costs of investments designed to improve resilience is typically a relatively straightforward exercise, more work still needs to be done to comprehensively assess the benefits of such investments. Although BCA typically requires translating benefits and costs into monetary values, resilience investments can also be evaluated using quantitative, non-monetary measures and qualitative descriptions to account for the full set of possible benefits and costs, including equity and distributional consequences.

To carry out resilience assessments, transportation agencies need high-quality data and analytic tools. Unfortunately, much of the data required for advanced analytic tools are not readily available today. Agencies need information on the characteristics of natural hazards and their likelihood in the location of existing and planned assets. They need access to science-based and updated projections about future impacts of climate change on natural hazards and on temperature and precipitation norms in these locations. They need strong asset management programs that include evaluations of asset vulnerabilities and estimation of functional values (i.e., criticality). They need mode-specific data and modeling tools to estimate the direct and indirect consequences of asset damage and loss of functionality. And they need data and modeling tools that can reveal the economic and social importance of the asset to users, directly affected communities, and the broader region. Where there are gaps in essential data and in the needed analytic tools, transportation agencies may need to tap expert judgment.

Pilot programs, often led by federal agencies, have played a crucial role in advancing practices that integrate resilience into decision making and have shown the way to making resilience-based decision making more routine. The Federal Highway Administration (FHWA) has been especially active in developing and piloting methods and tools that have increased the familiarity with resilience assessments among state and local transportation agencies. However, these programs remain limited in their scale and scope. Without the additional support of expanded pilot programs, transportation agencies are likely to continue to struggle with the translation of resilience from a concept to a decision criterion.

RECOMMENDATIONS

To motivate and facilitate the use of a systematic decision-making framework for resilience, more direction, prompting, and guidance are needed. Leadership from Congress and the U.S. Department of Transportation (U.S. DOT) will be critical to advancing the development and implementation of a systematic framework, including its relevant analytical tools, metrics, and supporting data. The five recommendations that follow are directed to Congress and U.S. DOT, but their aim is to strengthen the resilience practices and capabilities of thousands of state, regional, and local transportation agencies.

RECOMMENDATION 1:

To ensure the routine and deliberate consideration of resilience to support the selection of major transportation investments, **Congress should consider a requirement for which all projects that involve long-lived assets and that are candidates for federal funding undergo well-defined resilience assessments that account for changing risks of natural hazards and environmental conditions stemming from climate change. These assessments could be integrated into environmental impact assessments or other project evaluation efforts, such as during benefit-cost analysis. The level of analytical effort expected in these resilience assessments should be reasonably related to the cost of the project being considered.**

Each project's selection should include the results of analyses in which resilience benefits are calculated through a multi-step analytic framework that includes assessments of all plausible natural hazards and their likelihood, including simultaneous and cascading hazards; the vulnerabilities of the asset to damage and disruption from the hazards; and the adverse consequences from the damage and disruption to functionality as they impact the owners and users of the assets and the broader community.

RECOMMENDATION 2:

The Office of the Secretary of Transportation should promote the use of benefit-cost analysis for project justifications that take into account the resilience benefits estimated using the multi-step analytic framework recommended above. The benefits from adding resilience, in the form of reduced future losses, in relation to the life-cycle costs of doing so should be promoted as the basis for selecting investments in resilience.

Although the practice of BCA is often associated with an overemphasis on the benefits and costs that can be more confidently monetized, the nature of resilience impacts, coupled with the demands of practical decision making, call for analyses that are attentive to all important effects, whether represented in monetary, quantitative, or qualitative terms. The Office of the Secretary of Transportation (OST) should offer guidance on how important benefits and costs that cannot be reduced to monetary units can be appropriately incorporated in BCA. Such benefits and costs include those affecting equity and the distribution of impacts.

RECOMMENDATION 3:

The Office of the Secretary of Transportation should provide guidance to the U.S. Department of Transportation modal administrations on the development of analytic methods and tools for estimating resilience benefits that are applicable to transportation agencies in their respective modes.

The guidance should build on lessons learned from initiatives by FHWA and other federal and state agencies to pilot analytic approaches like the multi-step framework recommended above for use in assessing resilience on major transportation projects receiving federal funds. The guidance should point to the kinds of data and analytic tools required to perform each step in the assessments, and it should explain how the results can be used in BCA for decision making that incorporates resilience.

The development of guidance should encompass, to the extent possible, strategies designed to improve resilience through speeding response and recovery, as well as strategies that prevent damage and disruption to infrastructure assets.

RECOMMENDATION 4:

Congress should direct, and appropriately resource, the Office of the Secretary of Transportation to conduct a study to (1) define the types of data that transportation agencies need for resilience analysis in accordance with the framework recommended above; (2) identify potential sources of these requisite data; and (3) advise on possible means for making the data more suitable to this purpose, including filling key data gaps and ensuring timely data updates.

This study will require consultation with other federal agencies such as the Federal Emergency Management Agency, the National Oceanic and Atmospheric Administration, the U.S. Forest Service, and the U.S. Geological Survey, where much of the data needed for resilience analysis are maintained. Such consultation should cover how transportation agencies are to acquire the required information, including its format and level of detail, keep the information sufficiently up to date, and obtain additional information that is not readily available. This study should include consideration of the information requirements for addressing how climate change may worsen the impact of existing natural hazards. The study should note where new statutory authorities and appropriations may be required to enable these purposes.

RECOMMENDATION 5:

The Office of the Secretary of Transportation should coordinate with the modal agencies on the design and conduct of structured pilots to assess and demonstrate the applicability of each agency's guidance and suggested tools for estimating resilience benefits according to the recommended multi-step analytic framework.

FHWA's series of pilot programs for highway resilience analysis should be used as a model for these structured mode-specific pilots, which have led to increased state and local transportation agency familiarity with resilience analysis and to continual improvements in FHWA's guidance on analytic methods and appropriate tools.

The pilots should incorporate all of the elements of the analytic framework: identifying the assets, evaluating asset criticality, characterizing potential natural hazards and climate change effects, evaluating vulnerability of critical assets, characterizing consequences of hazard/climate on functionality, estimating risk, identifying options to reduce risk, conducting BCA, and providing advice for investment decisions. The pilot programs should also apply the framework to hazard event response and recovery, including organizational assets and strategies.

Appendix A

Study Committee Biographical Information

Joseph L. Schofer (*Chair*) is a professor emeritus of civil and environmental engineering at Northwestern University in Evanston, Illinois. At Northwestern, Dr. Schofer served as the chair of his department, the interim dean of the engineering school, and the director of the Infrastructure Technology Institute.

His research and teaching interests are in transportation policy planning; analysis, evaluation, and decision support for transportation and other infrastructure systems, including needs for and uses of data and information; and learning from natural experiments and disruptions. Since 2009, Dr. Schofer has hosted the Infrastructure Show, a monthly podcast on which he interviews infrastructure experts on problems, opportunities, and innovations in civil infrastructure systems.

He is a fellow of the Institute of Transportation Engineers, a life member of the American Society of Civil Engineers, and a member of the American Association for the Advancement of Science. He is actively engaged with the Transportation Research Board (TRB), currently chairing its Standing Committee on Data for Decision Making. In the past he chaired consensus studies for the Committee on Equity Implications of Evolving Transportation Finance Mechanisms, the Committee on Strategies for Improved Passenger and Freight Travel Data, and the Committee on Long-Term Stewardship of Safety Data from the Second Strategic Highway Research Program. He received the 2011 Roy W. Crum Distinguished Service Award from TRB. Dr. Schofer earned his B.E. from Yale University and an M.S. and a Ph.D. from Northwestern University.

Paolo Bocchini is an associate professor and the director of graduate programs in the Department of Civil and Environmental Engineering at Lehigh University. His research focuses on disaster resilient infrastructure systems, probabilistic analysis applied to civil engineering, and computational mechanics. Dr. Bocchini is the author of more than 80 manuscripts published as book chapters or papers in peer-reviewed international scientific journals and professional conference proceedings. One of his papers on infrastructure resilience is among the most read and cited in the American Society of Civil Engineers (ASCE) *Journal of Infrastructure Systems*. His research has been supported by the National Science Foundation, the National Institutes of Health, the U.S. Department of Defense, the Pennsylvania Department of Transportation, and companies in the private sector. Dr. Bocchini serves as an associate editor of the *Journal of Structural Engineering* and is a licensed Professional Engineer in Italy. He has been elected to the rank of Fellow of the Structural Engineering Institute of ASCE and is a member of the Engineering Mechanics Institute, Infrastructure Resilience Division, the International Association for Bridge Maintenance and Safety, the International Association for Life-Cycle Civil Engineering, and the American Institute for Sustainable Infrastructure.

Henry V. Burton is an associate professor and the Englekirk Presidential Chair in Structural Engineering in the Department of Civil and Environmental Engineering at the University of California, Los Angeles. His research is directed toward understanding and modeling the relationship between the performance of infrastructure systems within the built environment and the ability of communities to minimize the extent of socioeconomic disruption following extreme events. Dr. Burton is a registered structural engineer in the state of California. Prior to obtaining his Ph.D. in civil and environmental engineering at Stanford University, he spent 6 years in practice at Degenkolb Engineers, where he worked on numerous projects involving design of new buildings and seismic evaluation and retrofit of existing buildings. He is a recipient of the National Science Foundation's (NSF's) Next Generation of Disaster Researchers Fellowship (2014) and the NSF CAREER Award (2016).

Susanne E. DesRoches is the deputy director for infrastructure and energy at the New York City (NYC) Office of Resiliency and Office of Sustainability. She leads NYC's policies and programs focusing on adapting regional infrastructure systems to climate change and directs NYC's efforts to transition to 100% clean electricity by 2040. Ms. DesRoches leads the NYC Climate Change Adaptation Task Force, which works to identify climate risks and coordinate adaptation strategies, and oversees the development and implementation of the NYC *Climate Resiliency Design Guidelines*.

She was a chapter author for the Fourth National Climate Assessment and has testified before the U.S. House of Representatives Committee on Science, Space and Technology panel on the need for resiliency to prepare America's transportation infrastructure for climate change. Ms. DesRoches is actively engaged with the Transportation Research Board, currently as a founding member of the newly created Resiliency Section. Ms. DesRoches was previously the chief of resilience and sustainability for the Engineering Department at The Port Authority of New York and New Jersey. She holds a bachelor's degree in industrial design from Pratt Institute and an M.P.A. in environmental science and policy from Columbia University. Ms. DesRoches is on the faculty of Columbia University's Earth Institute and School of Professional Studies.

Alexander Heil is the vice president for research at the Citizens Budget Commission (CBC) in New York City. He manages CBC's research agenda and covers areas ranging from public-sector capital spending to infrastructure operations to government policy impacts. Dr. Heil is an economist with more than 20 years of experience in the private and public sectors. He joined CBC from The Port Authority of New York and New Jersey, where he held the position of chief economist for a decade. As the chief economist, Dr. Heil was responsible for developing and managing the agency's economic research and analysis agenda, helping to ensure that the agency's major investment and policy decisions were informed by sound economic principles and analysis. Specifically, he focused on capital prioritization of the agency's multi-billion-dollar capital plan, economic forecasting of transportation activities and revenues, and cost-benefit analysis of resilience investments. In addition, he played an active role in supporting sustainability and environmental analyses throughout the agency.

Prior to his appointment at the Port Authority, he was an economist for several engineering and consulting firms. He currently teaches at the Earth Institute and the School of International and Public Affairs at Columbia University and the Wagner Graduate School of Public Service at New York University.

Dr. Heil holds a Ph.D. in transportation economics from the University of South Wales in the United Kingdom. He received his bachelor's degree from Hawai'i Pacific University and his master's degree in economics from Golden Gate University.

Geraldine Knatz (NAE) is a professor of the practice of policy and engineering, a joint appointment between the University of Southern California (USC) Price School of Public Policy and the Sonny Astani Department of Civil and Environmental Engineering at the USC Viterbi School of Engineering. At the Price School, Dr. Knatz teaches as well as conducts research in affiliation with the METRANS Transportation Center. Dr. Knatz served as the executive director of the Port of Los Angeles from 2006 to January 2014. She was the first woman to serve in this role and made a significant impact through the creation and implementation of the San Pedro Bay Ports Clean Air Action Plan, an aggressive plan that reduced air emissions by combined port operations of more than 70% over 5 years. She established the Port of Los Angeles as the global leader in port sustainability and facilitated the introduction of new technology by creating opportunities for testing products geared toward customer needs and applications. The Clean Air Action Plan is recognized around the world for its innovation and success. Prior to directing the Port of Los Angeles, she served as the managing director of the Port of Long Beach, where she was responsible for development activities including the remediation of a California State Superfund site. She is the past chair of the American Association of Port Authorities and the past president of the International Association of Ports and Harbors, along with being the founding chair of the World Ports Climate Initiative.

Elise Miller-Hooks holds the Bill and Eleanor Hazel Endowed Chair in Infrastructure Engineering in the Sid and Reva Dewberry Department of Civil, Environmental, and Infrastructure Engineering at George Mason University. She is also an advisor to the World Bank Group and the founding editor-in-chief of Elsevier's journal *Sustainability Analytics and Modeling*. Prior to this, Dr. Miller-Hooks served as the program director of the National Science Foundation's Civil Infrastructure Systems Program, the lead program officer for the Critical Resilient Interdependent Infrastructure Systems and Processes solicitation, and a cognizant program officer on Civil, Mechanical and Manufacturing Innovation's Smart and Connected Communities initiative. She served on the faculties of the University of Maryland, The Pennsylvania State University, and Duke University. Her expertise includes disaster planning and response, including urban search and rescue, building and regional evacuation and sheltering, and crowd modeling; multi-hazard civil infrastructure resilience quantification and infrastructure protection investment; stochastic and dynamic network algorithms; mathematical modeling and optimization; transportation systems engineering; intermodal passenger and freight transport; maritime transport and port operations; real-time routing and fleet management; paratransit, ridesharing, and bikeways; and collaborative and multi-objective decision making. Dr. Miller-Hooks earned a Ph.D. and an M.S. in civil engineering from The University of Texas at Austin and a B.S. in civil engineering from Lafayette College.

Rear Admiral Ann C. Phillips (U.S. Navy, retired) is the Special Assistant to the Governor of Virginia for Coastal Adaptation and Protection. Since her appointment in October 2018, she has worked to implement the Governor's intent to protect and adapt Virginia's coastal region and to prepare Virginia for the current and future impact of sea level rise and climate change, including establishing a sea level rise planning standard for the Commonwealth; creating Virginia's first Coastal Resilience Master Plan; and improving collaboration, cooperation, and communication among federal, state, and local stakeholders. In this role, Rear Admiral Phillips has also testified before Congress. Recent testimony includes to the House Committee on the Budget, the House Transportation and Infrastructure (T&I) Maritime and U.S. Coast Guard Subcommittee, the House T&I Subcommittee on the Water Resources Development Act, and the Senate Special Committee on the Climate Crisis. Prior to joining the Governor's administration, she worked to address sea level rise and climate impact on national security at the regional, national, and international level. From 2014 to 2016 she chaired the Infrastructure Working Group for the Old Dominion University–convened Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Planning Project, focused on building a collaborative, whole of government, and community approach to address the impact of sea level rise across Hampton Roads. Preceding her work on climate impact and sea level rise, Rear Admiral Phillips served nearly 31 years on active duty as a Surface Warfare Officer. She had the honor to commission and command USS Mustin (DDG-89) and to command Destroyer Squadron 28. As a Flag Officer, she served on the Chief of Naval Operations' staff as the deputy director and then the director of the Surface Warfare Division, and her final Flag command at sea was as Commander, Expeditionary Strike Group TWO, including all of the Amphibious Expeditionary Forces on the East Coast of the United States. She holds an M.B.A. from the William & Mary Raymond A. Mason School of Business and a B.A. from the University of North Carolina at Chapel Hill.

Jose E. Ramirez-Marquez is the director of the Enterprise Science and Engineering Division and an associate professor in the School of Systems & Enterprises at the Stevens Institute of Technology. A former Fulbright Scholar, he holds degrees from Rutgers University in industrial engineering (Ph.D. and M.Sc.) and statistics (M.Sc.) and from the Universidad Nacional Autónoma de México in actuarial science. His research efforts focus on the development of mathematical models for the analysis and computation of system operational effectiveness—reliability and vulnerability analysis as the basis for designing system resilience. He also works at the intersection of evolutionary computation for the optimization of complex problems associated with system performance and design. His most recent research explores the interplay between data visualization and analytical decision making. In these areas, Dr. Ramirez-Marquez has conducted funded research for both private industry and government and has published more than 100 refereed manuscripts in technical journals, book chapters, and industry reports. He is an associate editor of the Institute of Industrial and Systems Engineering's *IISE Transactions*. He is a member of the Technical Committee on System Reliability for the European Safety and Reliability Association.

Victor Rivas is a senior transportation consultant for Jacobs. His consulting and research assignments focus mainly on asset management, transportation systems operations, and capital programming. His collaborative and multidisciplinary approach to problem solving has been applied to both the private and public sectors. Under a recent assignment, Mr. Rivas led a research team tasked with the development of the first *Federal Transit Administration (FTA) Transit Asset Management Systems Handbook*. Prior to joining Jacobs, Mr. Rivas led the team in charge of planning, programming, and managing the capital investment program for the fifth largest transit agency in the United States. Since 2012, Mr. Rivas has participated in the American Public Transportation Association Standards Program as a member of the State of Good Repair/Transit Asset Management Working Group. Mr. Rivas holds an M.S. in urban studies and planning from the Massachusetts Institute of Technology. He also holds a master's degree in urban planning and policy from the University of Illinois at Chicago and a B.A. from Southern Adventist University.

John (Jack) V. Wells is a retired transportation economist with 30 years of experience in transportation economics and policy making. He has worked in academic, congressional, and executive branch environments, and in both political and career positions. His work has involved a wide range of issues involving transportation safety, infrastructure investment, and economic regulation, and has included conducting hearings, drafting legislation and regulations, and presenting testimony. As the chief economist at the U.S. Department of Transportation, he focused on the application of economic analysis to issues of transportation congestion, infrastructure investment, and safety regulation, and gave particular attention to improving the state of the art of benefit-cost analysis to assess regulatory initiatives and infrastructure investments. Since his retirement from his position as the chief economist, he has remained active in the professional transportation and economics communities. Prior to this position, Dr. Wells served as the chief economist at the Bureau of Transportation Statistics, the deputy administrator of the Federal Railroad Administration, the Democratic staff director of the House Subcommittee on Railroads, Pipelines and Hazardous Materials and the staff director for the House Transportation Subcommittee on Investigations and Oversight, a senior economist at the U.S. General Accounting Office, and an assistant professor of economics at George Mason University.

He is active in the Transportation Research Forum (TRF), the Society for Benefit-Cost Analysis (SBCA), and on committees of the Transportation Research Board (TRB). He has reviewed papers and helped to organize conferences for TRF, TRB, and SBCA; served on committees overseeing ongoing TRB studies on inland water transportation, bicycle transportation, and the economic value of transportation infrastructure; delivered guest lectures on transportation economics; and spoken before the European Investment Bank in Luxembourg on employment effects of infrastructure investment.

Shawn Wilson is the Secretary of the Louisiana Department of Transportation and Development (LaDOTD). He was appointed to this position in 2016 after more than 10 years of executive service at LaDOTD. As the Secretary of LaDOTD, he oversees a multimodal transportation agency that administers programs for highways, aviation, transit, passenger rail, and ports and waterways. During his tenure as Secretary, Dr. Wilson has overseen many large investments in the state's transportation infrastructure, including securing and obligating nearly $150 million additional federal dollars for Interstate highway widening projects and other large investments to assist communities with alternative fueled transit assets, improve passenger rail service, and launch a bike share program in Baton Rouge. He is a member of the Transportation Research Board Executive Committee. Dr. Wilson earned a B.A. in urban and regional planning from the University of Louisiana and an M.P.A. and a Ph.D. in public policy from the Nelson Mandela School of Public Policy and Urban Affairs at Southern University.

Appendix B

Invited Speakers at Committee Meetings

MAY 13, 2020

Alasdair Cain, Director of Research, Development and Technology, Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation

Josephine Eckert, Professional Staff, Subcommittee on Transportation, Housing and Urban Development and Related Agencies, Committee on Appropriations, U.S. House of Representatives

JUNE 26, 2020

Angela Gladwell, Deputy Assistant Administrator for Risk Management, Federal Insurance and Mitigation Administration, Federal Emergency Management Agency

Robert Kafalenos, Environmental Protection Specialist, Sustainable Transportation and Resilience, Federal Highway Administration, U.S. Department of Transportation

Jeffrey Meek, Sustainability Coordinator, Minnesota Department of Transportation

SEPTEMBER 14, 2020

David Ferryman, Vice President of Sales, EVRAZ North America; Former CN Vice President of Engineering

Elizabeth Kemp, Risk and Resilience Program Manager, Colorado Department of Transportation

SEPTEMBER 17, 2020

Matthew Arms, Director of Environmental Planning, Port of Long Beach

Robert Germann, South Atlantic Division–Inland Program Manager, U.S. Army Corps of Engineers

Brendan Reed, Director, Planning & Environmental Affairs, San Diego County Regional Airport Authority

Dale Stith, Principal Transportation Planner, Hampton Roads Transportation Planning Organization

NOVEMBER 4, 2020

Andrew McMahan, Director of Emergency Management and Operations Support, New York Metropolitan Transportation Authority

Porie Saikia-Eapen, Director of Sustainability and Environmental Compliance, New York Metropolitan Transportation Authority

Appendix C

List of Selected Natural Hazard Databases

PORTALS TO DATA, TOOLS, AND TRAINING

U.S. Climate Resilience Toolkit

This toolkit contains a catalog with a wide array (nearly 150 items) of data, data viewers, and analysis tools that are useful for understanding and evaluating natural hazards related to climate resilience. See https://toolkit.climate.gov.

DigitalCoast
https://coast.noaa.gov/digitalcoast

Sea Level Rise Viewer
https://coast.noaa.gov/digitalcoast/tools/slr.html

Land Cover Atlas
https://coast.noaa.gov/digitalcoast/tools/lca.html

The Federal Highway Administration's Climate Change Adaptation and Resilience Tools
https://www.fhwa.dot.gov/environment/sustainability/resilience/tools

Climate Model Intercomparison Project (CMIP) Climate Data Processing Tool 2.1
https://fhwaapps.fhwa.dot.gov/cmip

The Federal Emergency Management Agency's (FEMA's) Hazus-MH: Earthquakes, Hurricanes, Floods, and Tsunamis
https://www.fema.gov/flood-maps/products-tools/hazus

The National Oceanic and Atmospheric Administration's (NOAA's) Climate Monitoring Tools
https://www.ncdc.noaa.gov/climate-monitoring

Temperature, Precipitation, and Drought
https://www.ncdc.noaa.gov/temp-and-precip

Climate Extremes Index
https://www.ncdc.noaa.gov/extremes

The U.S. Geological Survey's (USGS's) Coastal Change Hazards Portal: Extreme Storms, Shoreline Change, and Sea Level Rise
https://marine.usgs.gov/coastalchangehazardsportal

HAZARD-SPECIFIC TOOLS

FEMA's Flood Maps
https://www.fema.gov/flood-maps

Florida Commission on Hurricane Loss Projection Methodology
https://www.sbafla.com/method

National Integrated Drought Information System
https://www.drought.gov

NOAA's Precipitation Frequency Data Server (Atlas 14)
https://www.weather.gov/owp/hdsc

Sea, Lake, and Overland Surges from Hurricanes Model
https://www.nhc.noaa.gov/surge/slosh.php

USGS Earthquake Hazards Program—Data and Tools
https://www.usgs.gov/natural-hazards/earthquake-hazards/data-tools

Unified Hazard Tool
https://earthquake.usgs.gov/hazards/interactive

Seismic Design Tools
https://earthquake.usgs.gov/hazards/designmaps