NIST Special Publication
NIST SP 1295

NIST Transportation Systems and Functional Recovery Workshop Report

Christine Z. Beyzaei
Katherine J. Johnson
Sissy Nikolaou
Siamak Sattar
Jazalyn Dukes
Yalda Saadat

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1295

nehrp

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

NIST Special Publication
NIST SP 1295

NIST Transportation Systems and Functional Recovery Workshop Report

Christine Z. Beyzaei
Katherine J. Johnson
Sissy Nikolaou
Siamak Sattar
Jazalyn Dukes
Yalda Saadat
Earthquake Engineering Group
Materials and Structural Systems Division
Engineering Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1295

September 2023

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

NIST SP 1295
September 2023

NIST Technical Series Policies

Publication History

Approved by the NIST Editorial Review Board on 2023-09-15

How to Cite this NIST Technical Series Publication

Beyzaei CZ, Johnson KJ, Nikolaou S, Sattar S, Dukes J, Saadat Y (2023) NIST Transportation Systems and Functional Recovery Workshop Report. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) NIST SP 1295. https://doi.org/10.6028/NIST.SP.1295

NIST Author ORCID iDs

Christine Z. Beyzaei: 0000-0001-6724-1632
Katherine J. Johnson: 0000-0001-7199-8750
Sissy Nikolaou: 0000-0002-4094-2962
Siamak Sattar: 0000-0003-1096-7015
Jazalyn Dukes: 0000-0002-6114-7992
Yalda Saadat: 0000-0003-3959-1808

Abstract

Current codes and standards for seismic design are based on a life-safety approach, meaning that the focus is on saving lives when an earthquake occurs. The most recent reauthorization of the National Earthquake Hazards Reduction Program (NEHRP), P.L. 115-307 recognizes that to strengthen America's resilience to earthquakes, it is necessary to advance beyond a life-safety approach towards also preserving the functionality of buildings and lifeline infrastructure systems. This would enable community members to return to their homes and businesses, and resume community activities, more quickly after an earthquake occurs. One new target under development for extending performance beyond life safety is referred to as "functional recovery." A committee of subject matter experts organized by the National Institute of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA) identified options and recommendations for moving the Nation towards functional recovery in a report titled "*FEMA P-2090/NIST SP-1254: Recommended options for improving the built environment for post-earthquake reoccupancy and functional recovery time*", or the "NIST-FEMA Report." Recommendation 1 from the NIST-FEMA Report provides an overarching recommendation to "*Develop a Framework for Post-Earthquake Reoccupancy and Functional Recovery Objectives.*" Recommendation 4 from the NIST-FEMA Report addresses lifeline infrastructure systems, with the recommendation being to "*Design, Upgrade, and Maintain Lifeline Infrastructure Systems to Meet Recovery-Based Objectives*." Lifeline infrastructure systems include transportation systems such as roads, highways, bridges, rail, and ports.

This document summarizes a NIST-organized workshop held in September 2022 on transportation systems and functional recovery. The event enabled discussion, knowledge transfer, and interaction with subject matter experts from both research and practitioner backgrounds on mechanisms for improving functional recovery and resilience of transportation systems for earthquake events. Invited speakers were selected to provide representation from diverse groups and presentations were shared on both research and practical projects or programs, including from the Federal Highway Administration (FHWA). Informed by past projects and interactions with FHWA, the topical areas for presentations were designed to provide workshop attendees with an overview of cutting-edge research, practice, and ongoing federal programs to broaden perspectives and stimulate cross-disciplinary insights throughout the day. The workshop also included breakout sessions, report-outs, and discussion among workshop attendees on key questions to identify the current status, challenges, priorities, and future vision for transportation systems and functional recovery. This effort is a continuation of earlier efforts in developing the NIST-FEMA Report to explore options for functional recovery and is not intended to set any functional recovery goals or recovery times for transportation systems. It is intended provide insights on functional recovery and transportation systems and inform development of a functional recovery framework. This report details the discussion and important themes that emerged from the workshop. The insights gained from the workshop will help to identify research needs and paths forward to continue working toward Recommendation 1 and Recommendation 4 of the NIST-FEMA Report.

Keywords

Built Environment; Community Resilience; Critical Infrastructure; Earthquake Risk Reduction; Functional Recovery; Functionality; Lifeline Infrastructure Systems; Lifeline Services; Natural Hazard; Performance; Recovery-Based Objective; Safety; Transportation.

Table of Contents

List of Tables

List of Figures

Acknowledgments

The authors gratefully acknowledge the contributions of the individuals who participated in and helped organize this workshop.

Transportation Systems and Functional Recovery Workshop Report

1. Improving Post-Earthquake Performance

Current codes and standards for seismic design are based on a life-safety approach, meaning that the focus is on saving lives when an earthquake occurs. With this design approach, however, significant damage to the built environment and disruption of community functions and services may still occur. The most recent reauthorization of the National Earthquake Hazards Reduction Program (NEHRP), P.L. 115-307 recognizes that to strengthen America's resilience to earthquakes, it is necessary to shift toward preserving the functionality of buildings and lifeline infrastructure systems, so that community members can return to their homes and resume community activities more quickly after an earthquake occurs. The concept of a targeted performance state that extends beyond life safety is referred to as "functional recovery."

At the request of Congress, the National Institute of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA) identified options for moving the Nation towards functional recovery and submitted a report to Congress titled "*FEMA P-2090/NIST SP-1254: Recommended options for improving the built environment for post-earthquake reoccupancy and functional recovery time*" [1], referred to herein as the "NIST-FEMA Report."

The NIST-FEMA Report includes the following definition for functional recovery:

> *Functional recovery is a post-earthquake performance state in which a building or lifeline infrastructure system is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of a building, or the pre-earthquake service level of a lifeline infrastructure system.*

Figure 1 illustrates where functional recovery falls within a number of potential post-earthquake performance states for buildings, ranging from collapse to full functionality. It should be noted, however, that while the functional recovery post-earthquake performance state may exist immediately following the earthquake event, it may also require some repairs or time after an earthquake to achieve that state.

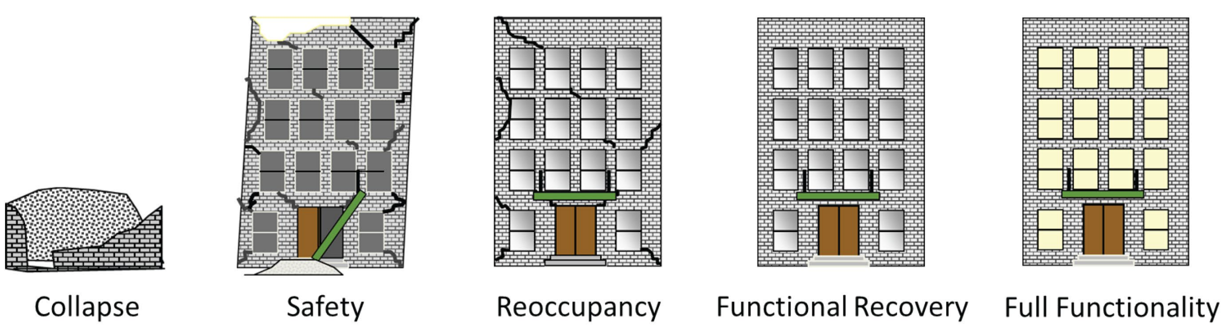

Figure 1. Illustration of Theoretical Range of Post-Earthquake Building Performance States (courtesy of R. Hamburger, from NIST-FEMA Report [1]).

The NIST-FEMA Report provides seven recommendations for improving the performance of buildings and lifeline infrastructure systems in terms of reoccupancy and functional recovery time. The focus of each recommendation is highlighted in Figure 2. The primary recommendation, Recommendation 1, from the NIST-FEMA Report was to develop a functional recovery framework, with three supporting recommendations shown on the right half of Figure 2 related to the built environment (new buildings, existing buildings, and lifeline infrastructure systems), and three supporting recommendations shown on the left half of Figure 2 that address the social and economic aspects including planning, education and training, and access to financial resources.

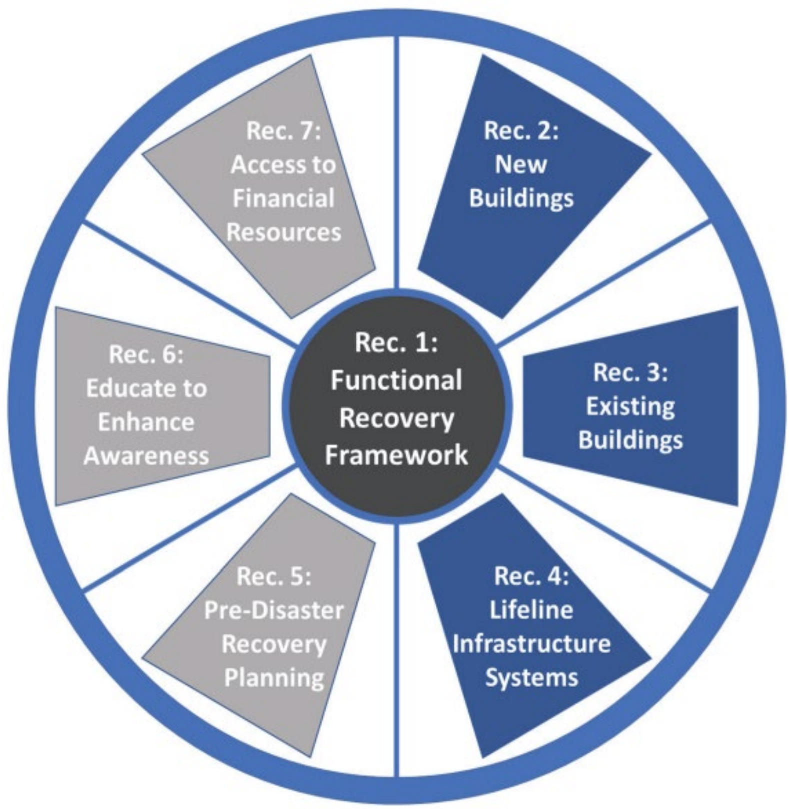

Figure 2. Recommendations for moving toward functional recovery (from the NIST-FEMA Report [1]).

1.1. Transportation Systems and Functional Recovery

Recommendation 4 from the NIST-FEMA Report addresses lifeline infrastructure systems, with the recommendation to "*Design, Upgrade, and Maintain Lifeline Infrastructure Systems to Meet Recovery-Based Objectives*."

Lifeline infrastructure systems include transportation systems such as roads, highways, bridges, rail, and ports, as well as other kinds of utility and critical lifelines systems such as water, wastewater, electricity, gas, and telecommunications. NIST has several ongoing projects related to functional recovery for lifeline systems, including water, electrical, and transportation. The focus of the workshop described in this report was on transportation systems and functional recovery and currently there are two ongoing efforts at NIST related to this topic: 1) a framework to enhance resilience of rail transit networks; and 2) a decision support tool for transportation investment planning. These efforts are described in the following subsections.

The workshop described in this report is a continuation of earlier efforts in developing the NIST-FEMA Report to explore options for functional recovery and is not intended to set any functional recovery goals or recovery times for transportation systems. It is intended provide insights on functional recovery and transportation systems and inform development of a functional recovery framework.

1.1.1. Ongoing NIST Effort – Framework to Enhance Resilience of Rail Transit Networks

NIST is developing a framework to enhance the resilience of urban rail transit systems [2]. Natural hazards such as earthquakes can result in devastating damage to distributed transportation networks (e.g., urban rail networks), affecting the lives and well-being of commuters that rely on their functionality. The recovery process may also take significant time. Thus, the system needs to be resilient to be able to restore to its pre-event state more rapidly. In this project, NIST is developing a framework to improve resilience through a set of computational steps. This includes collecting and processing data and developing algorithms to detect critical and vulnerable components in the system. The next step following identification of critical components is developing recommendations to protect vulnerable components of the system, improve the robustness and enhance the resilience of the system, which are the basis for speedy recovery during disruption.

The goal is to minimize recovery time by optimizing the recovery process and considering the impact of multiple factors including recovery cost, demographics, and practicality. The final step involves providing suggestions for standards and guidelines to shift from safety-based objectives to recovery-based objectives for the design of urban rail transit systems. Given that urban rail transit systems follow the network distribution mechanism and is a tangible example of transportation network, the methodology and technical approach is built upon network analysis and focuses on Complex Network Theory (CNT) which is a powerful tool to analyze the topology and dynamics of a network. Although the theoretical work is done on urban rail transit networks, the methodology can be generalized to other transportation systems such as roadways.

1.1.2. Ongoing NIST Effort – Decision Support Tool for Transportation Investment Planning

NIST is facilitating the development of an online tool that will contribute to strengthening America's infrastructure focused on transportation lifeline systems. The project will advance recent work by the U.S. Federal Highway Administration (FHWA) ("Framework for Infrastructure Resilience and Post-Hazard Response" - FHWA-PROJ-19-0034, report not yet published) and NIST Edge$, Economic Decision Guide Software [3], as well as FEMA's Hazus framework [4]. The project will combine these efforts into a single tool that will support decisions on how to maximize earthquake resilience of a highway network while optimizing the investment of financial resources.

This effort is directly addressing Recommendations 1 and 4 of the NIST-FEMA Report for functional recovery performance goals – specifically for transportation structures - that requires infrastructure to be maintained, or to quickly provide service to the population after natural hazard events.

The resulting decision support tool will allow users to plan investments for enhancing the earthquake performance and recovery time of bridge infrastructure within highway networks. This effort involves the development of indicators and metrics, reliable models for spatial-temporal risk analysis, and appropriate retrofit actions. The tool will contain four modules:

- Module 1: Asset identification in which users provide topology and location of set of bridges in a road network
- Module 2: Hazard mapping in which users define earthquake hazard
- Module 3: Damage and resilience assessment in which the tool assesses the loss and resilience score of the network
- Module 4: Investment optimization to enhance resilience in which the tool estimates the optimum plans to increase the resilience of the network

The tool is anticipated to assist stakeholders (e.g., municipal or regional resilience planners, engineers) in planning and prioritization for retrofit efforts.

2. Overview of Workshop

This section provides the goal and objectives for the workshop, agenda, and attendee summary.

2.1. Goal and Objectives

The purpose of this workshop was to discuss functional recovery and resilience of transportation systems for earthquake events, to share knowledge, and to interact with subject matter experts.

The workshop convened subject matter experts with both research and practitioner backgrounds in risk, resilience, and functional recovery of transportation systems, and was announced publicly via NIST's Events Calendar and LinkedIn profile. The announcement stated that participants would discuss ongoing efforts in developing functional recovery goals and decision tools for transportation systems, implementation of research assessment methodologies, and incorporation of transportation equity and climate resilience aspects. The announcement also noted that workshop participants would aim to assess challenges, including technical and stakeholder considerations, to developing functional recovery performance objectives for transportation systems.

The workshop was not intended to be educational, but rather to facilitate a focused discussion of critical issues in the subject area. Registration was open to the public, but the announcement identified ideal participants as having a strong background in functional recovery concepts and seismic analysis, risk assessment, or modeling of transportation systems, especially in relation to post-earthquake functionality needs.

The workshop objectives were to:

- Discuss ongoing efforts in developing functional recovery goals and decision tools for transportation systems
- Assess challenges to developing functional recovery performance objectives for transportation systems
- Delineate major categories of transportation systems and assess leveraging functional recovery categories/timelines/metrics for buildings in advancing functional recovery efforts for transportation systems

This workshop was a step in working toward meeting Recommendation 1 from the NIST-FEMA Report, which is to "*Develop a Framework for Post-Earthquake Reoccupancy and Functional Recovery Objectives,*" and Recommendation 4 from the NIST-FEMA Report, which is to "*Design, Upgrade, and Maintain Lifeline Infrastructure Systems to Meet Recovery-Based Objectives*." The insights gained from the workshop will help to identify research needs and paths forward to continue advancing topics related to Recommendations 1 and 4.

2.2. Agenda

The workshop agenda is included in Appendix A. The morning portion of the workshop consisted of presentations by NIST personnel and invited speakers. The afternoon portion of the workshop consisted of breakout sessions, report-outs, and discussion among the workshop attendees.

2.3. Attendee Summary

This workshop was the first in-person event held by the Earthquake Engineering Group at NIST since the onset of the COVID-19 pandemic. Twenty-two people registered to attend the workshop from across academia, industry, and government. Seventeen people attended the workshop in person; a list of the attendees is provided in Appendix B.

Information gathered at the workshop provided valuable insights into the attendees' perspectives on transportation systems and functional recovery, but some limitations should be noted. This was a single workshop, with open registration and a relatively small number of participants across different sectors, so the attendee perspectives should not necessarily be assumed to constitute a representative sample of any profession, geographic area, or population.

3. Presentation Sessions

The morning portion of the workshop consisted of presentations by NIST personnel and invited speakers on the topics of functional recovery and transportation systems.

The workshop was opened by Dr. Jason Averill, Division Chief for the Materials and Structural Systems Division at NIST. Dr. Averill provided an overview of NIST and key NIST organizations and efforts including the Engineering Laboratory, NIST's work on disaster-resilient buildings, infrastructure, and communities, and NIST's major efforts on earthquake risk reduction and functional recovery. Key publications related to these efforts include the NIST Community Resilience Planning Guide [5],[6] (released in 2015 following the President's Climate Action Plan) which forms the foundation for NIST's ongoing work in Community Resilience, the NIST Immediate Occupancy Report [7] (released in 2018, detailing what it would take for the nation to produce buildings that could be immediately occupiable following a disruptive natural hazard event), and the NIST-FEMA Functional Recovery Report [1] (released in 2021, detailing recommended options for improving the built environment for post-earthquake reoccupancy and functional recovery time).

Following the welcome presentation by Dr. Averill, an overview of Functional Recovery was provided by Dr. Sissy Nikolaou, the Group Leader for the NIST Earthquake Engineering Group. This presentation covered:

- the motivation for and definition of functional recovery,
- the need for functional recovery goals in transportation,
- current risks to transportation infrastructure in the United States, functional recovery performance targets and categories,
- the intersection of functional recovery with a code-based approach, performance-based design, and community resilience,
- ongoing NIST efforts on functional recovery,
- inspiration from FHWA frameworks,
- and development of decision support tools.

A key goal of this presentation was to provide an overview of functional recovery so that workshop attendees would be oriented from the same starting point for discussions throughout the day, and enable participants to have a shared basis for the day's discussion.

After the welcome presentation and functional recovery overview, the workshop included two presentation blocks featuring invited speakers on topics related to transportation systems and functional recovery. The presentation blocks are summarized in Table 1 and Table 2 below. The invited speakers were selected to comprise a diverse group with presentations on research and practical projects or programs covering a range of topics related to functional recovery and transportation systems, including representation from the Federal Highway Administration (FHWA). Two presentations focused on equity and climate change in relation to transportation infrastructure, to highlight the importance of these aspects in advancing functional recovery for transportation systems. The goal for the invited presentations was to provide workshop attendees with an overview of cutting-edge research, practice, and federal programs to broaden their perspectives and stimulate cross-disciplinary discussions and insights throughout the day.

The presentation abstracts and abbreviated presentation biographies are provided in Appendix C.

Table 1. Invited Speakers and Presentation Topics for Presentation Block 1.

Presenter	Presentation Topic
Dr. Rallis Kourkoulis *(Grid Engineers)*	Investing in highways' resilience: analyzing the value chain to maximize returns
Anibal Tafur *(Rice University)*	Resilience of Intermodal Freight Transportation Infrastructure Subjected to Seismic and Hurricane Hazards
Dr. Paolo Bocchini *(Lehigh University)*	Recovery models at different resolutions for transportation systems

Table 2. Invited Speakers and Presentation Topics for Presentation Block 2.

Presenter	Presentation Topic
Dr. Tierra Bills *(UCLA)*	Advancing Equity in Transportation Data, Models, and Measures
Derek Soden *(FHWA)*	Resilience in Highway Asset Management
Guillermo Diaz-Fanas *(World Bank)*	The Nexus between Climate-Smart Transport Infrastructure and Functional Recovery

Presenters were allotted a 30-minute timeslot and encouraged to allow up to 10 minutes for questions within their timeslot.

4. Breakout Sessions

The afternoon portion of the workshop consisted of breakout sessions, report-outs, and discussion among workshop attendees.

Prior to beginning the breakout sessions, an overview of the breakout session topics and objectives was provided by Dr. Siamak Sattar, Acting Group Leader for the NIST Earthquake Engineering Group. The overview by Dr. Sattar served to remind workshop attendees of key points from the functional recovery overview provided in the morning session and to guide attendees to consider the morning presentations in the context of functional recovery for the breakout session discussions. Figure 3 highlights the core needs for functional recovery framework development, which workshop attendees were instructed to consider during the breakout session discussions.

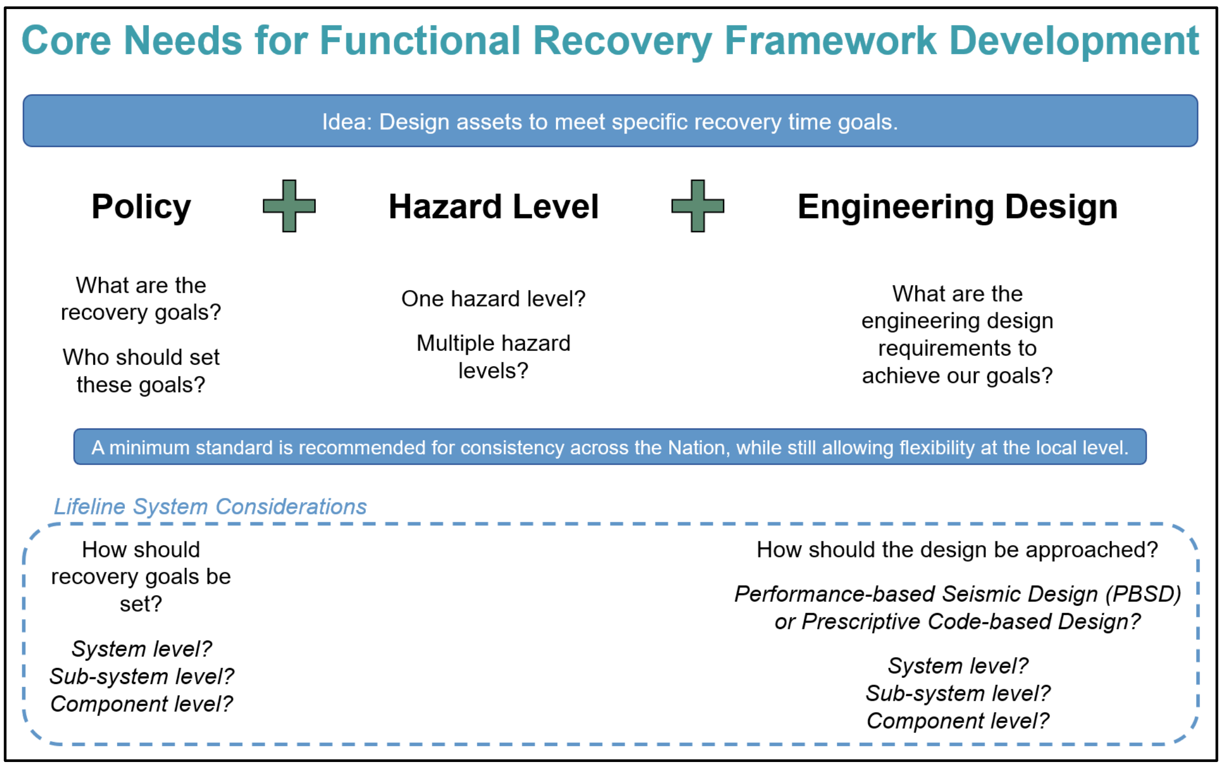

Figure 3. Core Needs for Functional Recovery Framework Development for Transportation Systems.

Prior to the workshop, attendees were also provided with a list of reference materials and additional related resources as background for the workshop discussions. This list is provided in Appendix D.

4.1. Objective and Process

The objective of the afternoon breakout sessions block was to discuss a series of questions focusing on the current status, challenges, priorities, and future vision for transportation systems and functional recovery. The objectives for the discussions were to:

- Discuss ongoing efforts in developing functional recovery goals and decision tools for transportation systems
- Assess challenges to developing functional recovery performance objectives for transportation systems
- Delineate issues relevant to transportation systems to advance development and implementation of a functional recovery (FR) framework

Given the broad nature of the topic of transportation systems and functional recovery, the following guidance was given for the scope of the breakout session discussions:

- Assume design level event/hazard
- Focus on the following transportation networks: bridges, roads, rail

Workshop attendees were sorted into two groups to facilitate discussions for the breakout sessions. Group assignments were randomized across attendee sector groups (e.g., academia, federal, consulting), targeting a random, but even, representation of attendee categories in the two groups. Attendees were provided with a handout containing the breakout session questions listed in the following section, and a moderator and notetaker were assigned for each group. Both groups received the same set of breakout questions. The moderator posed the breakout sessions to the group and guided the discussion to ensure that all attendees were able to participate, and that the discussion remained relevant to the breakout session questions. Following each breakout session, the two groups reconvened for "report-outs" where a volunteer from each group summarized the group discussion of the breakout session questions. An open discussion was then held among all workshop attendees on observations from the report-outs and any additional comments.

4.2. Breakout Session Questions

The questions posed during Breakout Sessions 1 and 2 are provided in the sections below. In the breakout session questions, the use of "we" refers to the broader community of people working on functional recovery. It is not intended to refer to NIST specifically.

4.2.1. Breakout Session 1 – "Current Status and Challenges"

The focus of Breakout Session 1 was on the current status and challenges for transportation systems and functional recovery. The questions were structured under two main topics: a) Functional Recovery (FR) Framework Development; and b) Metrics for Quantification and Assessment. The questions discussed under each of these topics are provided here:

Functional Recovery (FR) Framework Development

- Can you describe efforts (practice/research/planning) in the US or internationally that incorporate concepts or goals similar to a FR approach (e.g., recovery-based goals)?

- Do you currently prioritize system-level or component-level goals for transportation system design and upgrade/maintenance?
- The NIST-FEMA Functional Recovery Report (2021) advocates for a national FR framework. What challenges might you anticipate from the involvement of multiple authorities working together to set recovery goals for transportation systems?
- Do you feel a single FR framework is appropriate, or are multiple FR frameworks necessary to accommodate needs specific to particular sectors or infrastructure types?
    - How can we plan for alignment of recovery goals between different types of systems/networks (e.g., highways and commuter rail networks)?

<u>Metrics for Quantification and Assessment</u>

- What seismic (or other hazard) risk mitigation goals does your organization have or you know of? What do you use for monitoring and evaluation in order to meet these goals?
    - How does your organization currently identify/measure objectives, inputs, activities and outcomes for system upgrades or risk mitigation?
- What qualitative and quantitative metrics similar or related to FR (for example, the concept of "serviceability") are being used in transportation infrastructure projects and planning?
    - Based on current state, what are fundamental FR metrics that are/should be included in transportation design? (e.g., % of lanes open by a certain time; user satisfaction; etc.)? Are these related to a hazard level/type?

4.2.2. Breakout Session 2 – "Priorities and Future Vision"

The focus of Breakout Session 2 was on the priorities and future vision for transportation systems and functional recovery. The questions were structured under two main topics: a) Models, Tools, and Data; and b) Implementation and Adoption. The questions discussed under each of these topics are provided here:

<u>Models, Tools, and Data</u>

- Are there models/tools available or under development that could inform or be utilized for a transportation FR framework?
- What are the data needs for implementing models/tools of a transportation FR framework? What are the priorities for data collection, processing, storage and sharing? What are recommended protocols to meet these needs?
- Is there a need for open-source tools for FR assessment that include spatial network typologies and taxonomies for transportation infrastructure? Could these enhance our

understanding of transportation assets and systems performance in conjunction with high-fidelity engineering models that typically address life safety objectives?

- How can we measure the actual economic cost of implementing functional recovery goals and the benefit of avoided losses? How can we best model it? Do you envision this being part of an organization's financing plan and value-for-money analyses?

Implementation and Adoption

- To ensure consistent risk mitigation benefits across the nation, what are effective strategies to implement FR goals? Who should be involved in developing adoption mechanisms for those goals?
- What mechanisms can be used to implement a FR framework at the federal, state, county, and city levels? What are the biggest challenges to doing so?
- For using a decision-support tool like the NIST Transportation Tool, would you be most interested in optimizing performance for hazard-level targets or budget/schedule constraints?
- How can we prioritize meeting public and user needs within a FR framework that enhances performance goals beyond life safety?

4.3. Summary of Breakout Session Discussions

The diverse backgrounds of the workshop attendees, and the broad nature of transportation infrastructure, resulted in primarily high-level discussions prompted by the breakout session questions, consistent with the goals of the workshop. The discussion content was compiled and key points made by participants at the workshop are summarized under eleven discussion theme categories presented and discussed in more detail in the subsections below.

It should be emphasized that the content provided in this section represents high level themes elicited from participant discussions and key points shared by a diversity of individuals. As such, these points do not represent consensus opinion nor the perspective of NIST or any other federal agency, but are provided to help shape future thinking and action plans which can accommodate the complex and often conflicting priorities required to provision improved performance for the end user. Figure 4 shows the four breakout session focus areas in colored boxes, and underneath lists the resulting discussion themes, with colored lines mapping the relationships between the breakout session focus areas and the discussion themes. The points provided under each discussion theme section (4.3.1 through 4.3.11) represent ideas and suggestions which were highlighted as important or critical for advancing the potential for transportation systems to meet functional recovery goals.

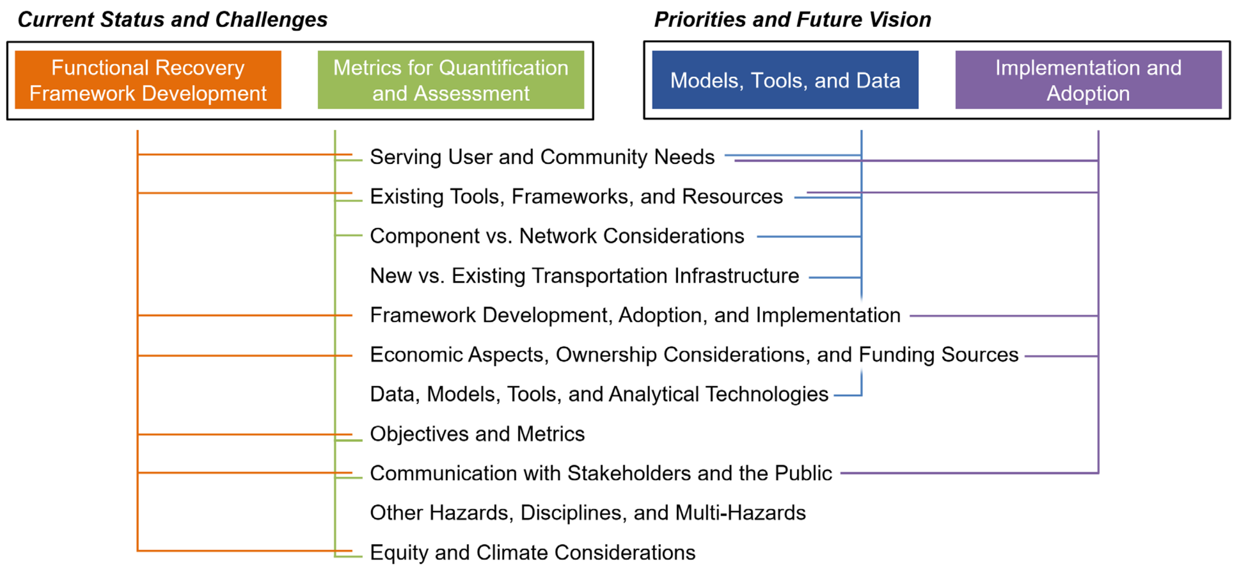

Figure 4. Breakout session focus areas and resulting discussion themes, mapping relationships between the breakout session topics and the discussion themes.

4.3.1. Serving User and Community Needs

The built environment, including transportation infrastructure, exists to serve the needs of users and the community. The key points and participant comments below reflect the discussion related to this topic.

- User needs and societal demands should be driving forces in developing FR goals.
- The context of the region should be considered (e.g., single hospitals vs. multiple hospitals in a region). Focus on the region and how accessible it is given the transportation infrastructure.
- User needs include sidewalks, streetlights, and characteristics of quality of service.
- The "Complete Streets" concept can be utilized, trying to measure the overall experience for users.
    - "*Complete Streets are streets designed and operated to enable safe use and support mobility for all users. Those include people of all ages and abilities, regardless of whether they are travelling as drivers, pedestrians, bicyclists, or public transportation riders…Complete Streets approaches vary based on community context.*" [8]
- Enhanced community participation is necessary to better meet community needs. The process used in regional planning often includes community members in decision making by sharing requirements and soliciting feedback at project development phases. However, public input is rarely sought for asset management plans. More involvement should occur at this phase and for long-term strategic planning and funding prioritization.

- Regional transportation planning processes need strengthening, with advances in decision-making for scoping (what is included) and participation (who is included), with additional mechanisms for feedback throughout the duration of the project.
- Bridges are also conduits for other lifelines (e.g., electricity and water), as well as pedestrian/bicycle/rail access, so these should be considered as part of functionality.
- Make sure there are grievance mechanisms, monitoring and evaluation during project implementation, and that stakeholders who raise grievances are able to participate in addressing related issues as they arise.
- Improve capacity for assessing and considering likely assets performance today vs. needs and desires for FR goals for FR performance.
- Accessibility, travel time, and comfort are key factors for users.
- The technical community and stakeholders need to engage hard-to-reach and underrepresented populations.

4.3.2. Existing Tools, Frameworks, and Resources

There are many existing tools, frameworks, and resources that relate to the functional recovery and resilience of transportation infrastructure systems. Existing resources, such as those listed below, should be leveraged where appropriate to build on the available body of work and literature. The key points and participant comments below reflect the discussion related to this topic.

- FHWA Resilience Frameworks and Programs ([9],[10],[11])
  - Focused on the system level, currently developing optimization tools, emphasis on incorporating resilience into risk/asset management.
- NIST's Community Resilience Center of Excellence has been developing policies that communities can use to improve resilience
- INCORE from NIST's Community Resilience Center of Excellence [12]
  - Open source and data platform for analysis and planning which utilizes system of systems modeling to assess scenarios, recovery and retention of population goals, and optimization routines at a city or regional scale; benefit dependent upon inputs selected.
- PRAISYS led by Lehigh University group (open source) [13]
- U.S. DOT Resilience and Disaster Recovery Tool Suite (open source) [14]
- FEMA Hazus [4]
- PEER Transportation Systems Research Program [15]
- National Cooperative Highway Research Program (TRB, AASHTO, FHWA) [16]
- NHERI Design Safe [17]

- San Francisco Bay Area Planning and Urban Research Association (SPUR) – Chris Poland; engineers and stakeholders are two branches [18]
- REDi (private sector, Arup, focused on buildings) [19]
- U.S. Resiliency Council (non-profit, focused on buildings) [20]
- U.S. DOT, and particularly FHWA, have many resources for performance-based seismic design for bridges
- AASHTO guidelines: based on structural performance, not system performance.

4.3.3. Component vs. Network Considerations

Transportation infrastructure typically consists of complex systems with individual components and network considerations. Design approaches are often based on the components, but communities may be most impacted by performance of the network. The key points and participant comments below reflect the discussion related to this topic.

- Design is typically done at the component level, and performance of the components determines performance of a bridge
- Majority of efforts so far are based on the component level.
- Redundant systems or alternative travel paths/modes can provide options and may reduce the need to design stronger components in one location in a system or network.
- Performance of the component under typical conditions generally drives upgrades, not performance under hazard.
- FHWA tracking occurs at the element level, deterioration is targeted.
- Monitoring and setting goals tend to be system-oriented (e.g., network performance, traffic).
- There is a need for a mix of both component and network considerations. Individual components should work but there is also a need to prioritize maintenance and repair based on regional-scale dependencies and interactions which more greatly influence ability to provision societal needs and meet recovery goals.

4.3.4. New vs. Existing Transportation Infrastructure

Transportation infrastructure is subjected to weather and environmental fluctuations, which may result in significant deterioration over time. The deterioration process for existing infrastructure is not well captured by available data and models, although inspections often reveal significant differences in new vs. existing infrastructure. The key points and participant comments below reflect the discussion related to this topic.

- Deterioration of existing infrastructure and condition at time of earthquake is a major factor in performance of infrastructure.

- Need for inspection of deterioration to establish "current" state and collect data. [could use new tools/technologies like unmanned aerial vehicles (UAVs, also known as drones)]
- Inspection is primarily visual inspection, based on structure type, which may not reveal the full extent of deterioration.
- Bridges often need to be closed due to condition, without consideration for the population served. Assessment of impacts may be improved by factoring in potential population-specific impacts.
- In addition to new and existing infrastructure, rehabilitated or retrofitted existing infrastructure is an important third category that should be considered.
- Majority of transportation infrastructure is already built so there may be limited opportunities to introduce upgrades and retrofits.
- Is it ok that we have different expectations for performance and recovery for new vs. existing infrastructure?
- No consensus or benchmark models exist for deterioration of infrastructure, leading to widely varied assumptions.
- Strong need for a decision support tool that enables consideration of how existing structures are performing or anticipated to perform in a hazard scenario.

4.3.5. Framework Development, Adoption, and Implementation

Achieving functional recovery for transportation infrastructure systems will require development of a functional recovery framework(s), followed by adoption and implementation at state and local levels. The key points and participant comments below reflect the discussion related to this topic.

- A key point of spirited discussion was whether different systems (e.g., highways vs. commuter rail) need different "frameworks" or whether a unified, overarching approach would be preferable. Commentary included the following:
  - The same recovery goals cannot be applied for all types of transportation infrastructure and the design requirements are different, so establish a methodology that can be applied for different types of transportation infrastructure. Multiple frameworks were seen to be too complicated and undesirable, with a preference for figuring out how to make one overarching framework tenable.
  - For different types of systems and networks, there is a preference to keep the underlying methodology the same, but the criteria may be different.
  - Perhaps determine the framework, but don't set specific goals, for example keeping the underlying methodology the same, but with different criteria.
  - Different systems need different "frameworks." Determine the framework, but don't set the goals for the systems.

- Federal agencies and major organizations need to be involved in scoping and development of the FR framework, but effort from other entities is necessary for establishing policy targets and hazard parameters.
- Institution building (building capacity through cross-sector strengthening) will be necessary, with special attention to incorporating up from the local community level.
- Clear leadership at the federal level (for example, a FR national-level collaboration), which engages organizations at other levels, would be helpful for wide-scale adoption. Let states decide whether to make a requirement but provide supporting information and evidence. Government agencies may be able to build FR into discretionary funding requirements. Multilevel involvement of government agencies is often considered integral for resilience.
- Federal agencies' mandates are generally broad and don't provide for specifying how to do things, but agencies can motivate or encourage implementation of good practices.
- Implementation mechanisms include a range of options including: codes and standards, financing incentivization, guidelines and case studies, or scenario planning.
- When possible, the best approach is to translate guidance and best practices into the appropriate codes and standards (e.g., such as building codes for buildings), for adoption by states.
  - Difficult to move straight to code adoption, first need to convince it's the right thing because you're expanding the scope of design to consider recovery past life safety. Need to communicate the importance of expanding scope of design to go beyond the life safety target to incorporate recovery in order for adoption in code to be compelling.
  - However, states may push back on adopting latest codes so it's a good idea to do workshops in each state.
  - If something is seen as a burden, there will be no votes to get it in the code. So it is also important to do outreach to support adoption at the more local level.
- For new infrastructure, once something is in a design standard, it can be mandated.
- For existing infrastructure, there is no mandate for re-evaluation or retrofit, and no authority to require that by FHWA although they can support efforts.
  - "Retrofit" of existing infrastructure happens through the **asset management approach**. Allocate funding towards resilience or functional recovery-based projects. Asset management approach is how FHWA bridge program is implemented, so FR goals could be implemented there to address needs of existing infrastructure.
- Federal agencies can demonstrate leadership by proactively managing their inventory of assets (for example, by complying with Executive Order 13717 [21]).
- **Need to develop case studies to document how FR is useful.**
- Assess the services that are actually being delivered by the transportation infrastructure and use that as the basis for the economic analysis and funding approach.

- State DOTs have the authority to set performance/recovery goals, need to be approved and reviewed every two years (asset management for existing infrastructure). FR goals could be put in asset management plans, which FHWA approves.
- The hazard level and budget constraints need to be considered simultaneously.
    - The burden for non-seismic (or low to moderate seismicity) areas is often on determining the hazard and seismic design will lead to the same details as otherwise would have been required. In these cases, instead of focusing on the hazard itself encourage good detailing practice for design and construction.
    - Getting states in low to moderate seismicity regions to participate will be a challenge. They may worry about added costs. Could instead just use good detailing work (e.g., bridges).
- Unfortunately, experiencing a big earthquake event is often what motivates people to make big changes.
- Resilience tables that include the preliminary definition of the target and separate out contributions of technical people, society, and politicians are helpful resources.

4.3.6. Economic Aspects, Ownership Considerations, and Funding Sources

The successful adoption and implementation of a functional recovery framework will be heavily influenced by economic aspects, ownership considerations, and the availability of funding. The key points and participant comments below reflect the discussion related to this topic.

- Typically, all activities must be “economically sound” for funding allocation. This includes analysis for sustainability, FR, resilience, etc.
- The business case for resilience is a major issue. Proponents should be able to make the business case for resilience.
    - However, the analysis should also consider the many complex factors involved and different time horizons for returns on investment and net benefits.
- The benefit cost ratio must be greater than one, which is a challenge for resilience projects.
- Traditional cost-benefit analysis may not be applicable for rare events, look at different tools to overcome challenges (e.g., blended finances).
- Consider a conditional benefit cost analysis, for “if this event does happen.”
- Consider a multiplier in economic analysis for overall costs to a community.
- Insurability needs to be taken into account.
- Conduct more detailed assessments for economic impact in a community to enhance calculations of return on investment and avoided losses.
- Estimate incremental costs and total costs to provide better options in the assessment and evaluation phases.

- There is a difference between benefit cost analysis (typically deciding to fund or not) and formula funding, which is geared towards optimizing funding across a portfolio dedicated to a specific goal.
- Improve financial viability through using different scenarios or multihazard analyses.
- Public-private partnerships are an option for when public funds are not sufficient.
- Financial and insurance related timelines may differ from infrastructure design life or actual use life. There is a conflict between longer-term goals vs. short-term funding timelines.
- Build in lifetime potential negative effects into analyses (e.g., environmental contamination in an event scenario).
- Financers will look at key performance indicators (KPIs) in deciding whether or not to pay out. These are commonly used for climate-related projects and could be referenced for examples in this area.
- Project financial documents, including economic analyses, should be made publicly available in all cases where members of the public utilize or benefit from the asset.
- There is a need for improved decision support tools that incorporate economic aspects.
- Develop discount rates for use in benefit-cost analysis.
- Use discretionary funding programs to implement FR requirements.
- Provide financing incentives to achieve FR goals.
- Require that green or resilience bonds incorporate FR goals.
- Budget is often the primary constraint for a project, but the priority instead should focus on user needs for services and functionality.
- Challenges with public vs. private ownership of transportation infrastructure.
- Transportation tends to be more publicly owned than buildings, lifelines, or other built environment, so theoretically it should be easier to implement FR goals.

4.3.7. Data, Models, Tools, and Analytical Technologies

Data, models, tools, and analytical technologies are critical for functional recovery assessment. The key points and participant comments below reflect the discussion related to this topic.

- There is a lack of comprehensive geographic data for infrastructure.
- There are challenges in obtaining and using data. Issues regarding data policy difficulties, access, authorizations, security.
- Technical and stakeholder communities need reasonable and open-source tools for functional recovery assessment, including a larger portfolio of fragility curves.
- Think of what kind of additional data and coordination are needed to support implementation.

- Need to enhance the availability of data, and willingness and capacity to share data. Need for open data. Lots of examples of initiatives in open data and of interagency coordination, on which to draw. Open data requires procedures for secure and appropriate management.
- Data that should be public are not easily accessible, often have to go to the authorities for access. Sometimes data are considered sensitive.
- Data sharing through NSF NHERI DesignSafe – important tool for curation, sharing, and assigning DOI to data. But these datasets are not peer reviewed or subjected to quality control processes so mechanisms to evaluate data are needed.
- Extensive discussion about fragility curves and issues that arise due to lack of appropriate fragility curves. There is a need to develop mechanisms for incorporating fragility into asset management processes in order to better optimize spending.
- Hazus [4]: A publicly available tool that can be broadly applied, which covers multiple hazards and topics. But seen as inadequate for specific in-depth analyses due to lack of updated fragility curves and other aspects.
- Private companies and the insurance industry may have large libraries of fragility curves and advanced models available.
- Clear need for better incorporation of geotechnical and geological data.
- **Publicly funded data collection should result in publicly available data.**
- Variation in quality of data, based on resources and training of municipalities.
- Data management is key. Sensors and cameras are in place in many areas but managing that data is challenging.
- Instrumentation and real-time data via sensors, etc. would be very helpful.
- Need data on repair times and costs, downtime, and long-term recovery. Data are not readily available and challenging to estimate. Issues with not sharing data, proprietary data. Surveys for stakeholders is key to getting repair time data. Need to find people on the local level who can grant access to that data.
- Typologies and taxonomies should be used to inform analysis.
- Google has huge amounts of data, should partnerships be attempted? Streetview, satellite imagery, going back over 20 years in some cases, often highly detailed and commonly used in engineering practice as a primary data source. User data or other information?
- Vulnerability modeling.
- What other methods are available to develop tools that are able to reduce costs?

4.3.8. Objectives and Metrics

Clearly defined objectives and metrics will assist in engineering, social, and financial analyses, and enable communities and stakeholders to determine whether functional recovery goals for transportation infrastructure are being met during the aftermath of an earthquake. The key points and participant comments below reflect the discussion related to this topic.

- There is a need to better define the objective for the component within the system, network, or community – access, mobility, connectivity.
- Metrics may differ depending on time horizon (e.g., long-term vs. short-term indicators, and intermediate indicators).
- Both quantitative and qualitative metrics can be useful and appropriate depending on the situation.
- Need further development of metrics based on user costs, equity, connectivity, travel time, return to traffic.
- Choose specific metrics that are relevant to goals, and which can serve to motivate action (e.g., relevant to preventing population dislocation).
- Current transportation infrastructure projects and planning primarily aim to restore pre-event functionality.
- When choosing functionality metrics, satisfy the demand *after* the event has occurred rather than under "normal" conditions.
- Additional use of transportation infrastructure as conduit for other lifelines, pedestrians, and bike lanes, access to services, should also be considered as part of the functionality in addition to the primary purpose or use of the transportation infrastructure.
- "Indirect benefit" measurements should also be highlighted. These represent hard to measure benefits to users.
- Important to factor in resilience created through the project (impact on community, risk associated with the project), and not just resilience of the project on its own.
- What is the basis for setting priorities?
- What is being measured in terms of prioritization?
- Use existing metrics where possible – functionality metrics, recovery metrics?
- Tailor metrics for FR to community needs rather than regular industry metrics (e.g., port throughput vs. satisfying demand after earthquake).
- Barriers to setting goals include using metrics that are intuitive to decision makers, but are difficult to translate into measurements/data (more complex but more representative).
- Everything is typically converted into/measured by a dollar amount (e.g., truck traffic, heavy traffic) which is used to compare projects. However, there is no dollar amount available to account for important characteristics such as historical importance or pedestrian use.
- Objectives and constraints should be included in optimization analyses.

4.3.9. Communication with Stakeholders and the Public

Communication between the technical community, stakeholders, and the public will be key at all stages of planning, implementation, and long-term management for functional recovery of transportation systems. The key points and participant comments below reflect the discussion related to this topic.

- Communication with stakeholders and the public will be critical for implementing FR goals in communities.
- Stakeholder surveys should be used to identify data needs for implementing models and tools for transportation FR framework, as well as priorities for data collection, processing, storage, and sharing.
- The technical community needs to be able to quantify and communicate the benefits of FR for transportation systems, and the business case for FR.
- Make sure there is adequate representation from community, state, investors, owners, private sector, as part of the decision-making process, and be able to communicate to the public about this involvement and the credibility of FR goals due to stakeholder buy-in.
- Learn and understand how FR is perceived by the public and adapt communication methods to address misconceptions and accommodate concerns and interests.

4.3.10. Other Hazards, Disciplines, and Multi-Hazards

There may be data, resources, and information from other hazards and disciplines that can be leveraged for seismic functional recovery efforts. Such information would also assist in multi-hazard analysis that includes earthquake events. The key points and participant comments below reflect the discussion related to this topic.

- City, regional, and global climate scenarios could provide framework and metrics examples.
- Decision support tools for climate hazards can be integrated with FR and other multi-hazard performance goals to be more holistic and useful.

4.3.11. Equity and Climate Considerations

Issues of transportation equity and climate resilience should factor into ongoing functional recovery efforts. The key points and participant comments below reflect the discussion related to this topic.

- Everyone agrees that equity, environmental concerns, and resilience are important considerations, but benefit and cost provide critical constraints which may drive most decision-making or investment programs.

5. Key Takeaways from the Workshop

Workshop attendees emphasized the benefit of having participants from different sectors, which led to open and engaging discussions on a wide range of topics related to transportation systems and functional recovery. The following conclusions (in bold) have been synthesized from the discussion summary in Section 4 and are intended to convey the key takeaways from the workshop.

Throughout the workshop, an overarching observation from participants was that improving communication is critical for making progress on functional recovery goals, both within the technical community and with the public and stakeholders. Effective audience-appropriate communication methods should be considered an integral component for each of the key takeaways listed below.

5.1. Socio-economic analysis and data are critical for advancing functional recovery for transportation systems.

Transportation systems differ from other distributed infrastructure networks such as water or electrical systems due to the method of user engagement, user choice, and system redundancy. The selection of transportation system type and pattern of usage is also heavily dependent on social and economic factors. Workshop participants noted that effectively advancing functional recovery efforts for transportation systems will require significant socio-economic analysis and data, including for sectors, areas, or populations that may have previously been excluded from such analysis or datasets. The methods of data collection and populations or transportation systems included in data collection efforts will directly influence model development, analysis, and recommendations for metrics and planning strategies. Future efforts to advance functional recovery for transportation systems should take a broad approach to ensure that socio-economic analysis and data capture the full spectrum of users in a community and how those users interact with transportation infrastructure.

5.2. Making the business case for functional recovery will greatly assist with implementation efforts.

Workshop participants noted that the societal benefits of functional recovery goals are clear, but that altruism may not be a sufficient motivator for successful implementation in practice, especially in areas dealing with limited funding resources and multiple hazards (e.g., hurricanes, wildfires, floods). Participants heavily emphasized showing the economic benefits of functional recovery as a method to motivate implementation efforts across all types of transportation systems and all levels of governance and ownership. To that end, stakeholders will need robust investment analysis tools to understand where and how to allocate available resources across a network or region.

5.3. A unified methodology at the national level, with requirements determined at the state and local level, will encourage the broadest adoption.

Workshop participants engaged in a spirited discussion regarding functional recovery framework development, adoption, and implementation, noting that a proposed framework would need to be adopted at the state and county levels to ensure impact across the nation. Recognizing the variability in transportation systems, applicable codes or guidance documents, user engagement, and ownership/operation/management structures across the nation there was a general consensus among participants on the need for publicly available frameworks, methodologies, and tools to support decision making by communities and stakeholders, which could be adapted for different transportation system types and regions. Participants noted that national differences in infrastructure age and condition, seismicity levels, and available analytical models will also affect the implementation of a proposed framework or methodology. This is consistent with observations from the NIST-FEMA Post-Earthquake Functional Recovery Workshop Report [22] wherein "*participants identified a need for a national functional recovery framework to help guide individual communities as they devise plans that can be actionable at the local level*" "*participants voiced a preference that this guidance be flexible and adaptable such that it can be easily tailored to incorporate local community needs and values*." A key role for federal agencies could be to develop tools which will help states make informed decisions. Such tools could be developed by working closely with state-level stakeholders for a range of different transportation system types.

5.4. User needs and regional context should drive the development of functional recovery objectives and metrics for transportation systems.

The perceived performance of a transportation system can vary significantly depending on user needs and regional context. In major cities, urban rail may be a critical component of regional transportation, whereas in suburban areas highways and local roads may be most critical. For cities that act as commercial hubs, port facilities, freight rail, or airports may be critical not just for that city alone but also for cities that receive shipments from those locations, with potentially cascading impacts outside the immediate region. Workshop participants noted the diversity and complexity of transportation systems and networks, along with the complexity of potential impacts. Participants placed a strong emphasis on understanding user needs and regional context when developing functional recovery objectives and metrics for transportation systems, highlighting the important role of stakeholder and community involvement in that process.

5.5. Data collection, system monitoring, and model development are key, but should build on existing resources and result in open-source tools.

Workshop participants noted that data collection, system monitoring, and model development are key for both pre-event planning/preparedness and for post-event response. Participants noted that many existing resources and models are available but not readily accessible or easily implemented by communities or practitioners, so further efforts should aim to leverage and build on existing resources while improving access and usability for these resources. Participants placed a strong emphasis on the need for open-source tools and data while acknowledging that security concerns may exist for openly sharing of some details of transportation infrastructure systems.

5.6. Seismic performance of aged existing infrastructure is a critical research need.

Workshop participants noted that in many places across the U.S., transportation infrastructure has been in place for years, if not decades, and that functional recovery goals should consider the potentially deteriorated condition of aged existing infrastructure. The American Society of Civil Engineers (ASCE) 2021 Infrastructure Report Card paints a grim picture regarding the age and condition of roads, bridges, and transit systems [23]. The seismic performance of aged transportation infrastructure is not well characterized and is a critical research need to provide realistic inputs for modeling and analysis. Efforts to achieve functional recovery performance goals will need to consider the current state of transportation infrastructure assets, not just "as constructed" or "as new" states for performance assessment.

6. Summary and Future Work

Improving the earthquake resilience of our communities and moving beyond life safety performance objectives will take time and significant effort. Working toward functional recovery will help to improve the performance of buildings and lifeline infrastructure systems, which will support key community functions and aid in recovery following an earthquake event.

In the NIST and FEMA report to Congress, "FEMA P-2090/NIST SP-1254: Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time" [1], Recommendation 1 addresses development of a functional recovery framework and Recommendation 4 addresses lifeline infrastructure systems. Transportation systems are critical lifeline infrastructure systems. As part of broader work under Recommendation 1 and Recommendation 4, NIST conducted a workshop to discuss functional recovery and resilience of transportation systems for earthquake events, to share knowledge and interact with subject matter experts. A one-day in-person workshop was announced publicly and held in September 2022 in Rockville, MD with a diverse group of workshop attendees from federal and state agencies, academia, and industry. The workshop content and breakout session discussions are summarized in this report. Workshop objectives included discussion of ongoing efforts in developing functional recovery goals and decision tools for transportation systems, assessing challenges to developing functional recovery performance objectives for transportation systems, and leveraging existing resources and ongoing functional recovery efforts to advance functional recovery efforts for transportation systems. Key takeaways from the workshop included a need for socio-economic analysis and data; business case analysis; emphasis on a unified methodology at the national level with requirements determined at the state and local level; consideration of user needs and regional context; improved data collection, system monitoring, and model development that builds on existing resources to create open-source tools; and a critical research need to study seismic performance of aged infrastructure. Readers are encouraged to refer to the NIST-FEMA Report [1] for a more complete explanation of functional recovery and the recommended options for improving the built environment.

The workshop described in this report represents a starting point for important topics that need further exploration as the concept and goals of functional recovery continue to be developed.

Building on this work, future workshops could more systematically focus on specific types of transportation systems and stakeholder groups to obtain feedback and input on specific goals, anticipated post-earthquake needs, organizational structure, resource availability, infrastructure investment planning, and earthquake resilience strategies. Future research efforts can draw on the key takeaways from this workshop to help guide the development of new projects such as surveys to collect equitable socio-economic data, fragility curves for aged infrastructure, open-source network modeling, economic analyses considering underserved populations, and technical design, retrofit, or maintenance criteria for performance under different hazard levels.

Through a multifaceted approach including research, stakeholder input, and coordinated efforts on implementation and adoption, progress toward achieving functional recovery for buildings and lifeline infrastructure systems, including transportation systems, will continue. Over time, this will enable communities to be better positioned for response and recovery when future earthquakes occur.

References

[1] NIST-FEMA (2021). Recommended options for improving the built environment for post-earthquake reoccupancy and functional recovery time, FEMA P-2090/NIST SP-1254, Joint publication by FEMA and NIST. https://doi.org/10.6028/NIST.SP.1254

[2] Saadat, Y., Cook, C., Debock, D.J., Sattar, S., Nikolaou, S. (2023). Vulnerability Assessment of Infrastructure Networks Following Earthquakes: The Fundamental Step to Assess Network Resilience and Functional Recovery, *14th International Conference on Applications of Statistics and Probability in Civil Engineering*, Dublin, Ireland.

[3] Helgeson, J.F., Zhang, P.J. (2020). Economic Decision Guide Software (EDGe$) Online Tutorial: Wildland-Urban Interface (WUI) Case Study, NIST Special Publication 1260.

[4] Federal Emergency Management Agency (FEMA), (2022). Hazus | FEMA.gov. fema.gov/flood-maps/products-tools/hazus (Accessed February 16, 2023).

[5] NIST (2016). Community resilience planning guide for buildings and infrastructure systems – Volume I and II, NIST SP-1190. http://dx.doi.org/10.6028/NIST.SP.1190v1 and http://dx.doi.org/10.6028/NIST.SP.1190v2.

[6] NIST (2020). Community resilience planning guide for buildings and infrastructure systems – a playbook, NIST SP 1190GB-16, https://doi.org/10.6028/NIST.SP.1190GB-16.

[7] NIST (2018). Research needs to support immediate occupancy building performance objective following natural hazard events, NIST SP-1224. https://doi.org/10.6028/NIST.SP.1224

[8] U.S. Department of Transportation (2015). *Complete Streets. U.S. Department of Transportation*. Available at https://www.transportation.gov/mission/health/complete-streets

[9] Federal Highway Administration (FHWA), (2023). Bridges & Structures, Structures, Seismic and Multi-Hazard Resilience Program: https://www.fhwa.dot.gov/bridge/seismic/ (Accessed July 7, 2023).

[10] Federal Highway Administration (FHWA), (2023). Bridges & Structures, Geotechnical Engineering, Geohazards Program: https://www.fhwa.dot.gov/engineering/geotech/hazards/ (Accessed July 7, 2023).

[11] Federal Highway Administration (FHWA), (2017). Vulnerability Assessment and Adaptation Framework, Third Edition. Office of Planning, Environment, and Realty, FHWA-HEP-18-020, https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf (Accessed July 7, 2023).

[12] van de Lindt, J.W., B.R. Ellingwood, H. Cutler, P. Gardoni, J.S. Lee. (2019). "The structure of the Interconnected Networked Community Resilience Modeling Environment (IN-CORE)." Proceedings of the *2nd International Conference on Natural Hazards and Infrastructure*, 23-26 June, 2019, Chania, Greece.

[13] The PRAISys Team (2018). "Probabilistic Resilience Assessment of Interdependent Systems (PRAISys), (Nov. 5, 2018).

[14] Arthur, D., Badgley, J., Flynn, D., Gillham, O., Gilmore, M., Herzig, P., Lewis, K.C., Oberg, A., Reese, G., Smith, S., and Zhang, K. (2022). The Resilience and Disaster Recovery Tool Suite: Technical Document Version 2022.1.1. Volpe National Transportation Systems Center, Cambridge, MA, 2022. DOI: 10.21949/1527574 Rev. 1.

[15] UC Berkeley (2023). Transportation Systems | Pacific Earthquake Engineering research Center. https://peer.berkeley.edu/research/transportation-systems (Accessed February 27, 2023).

[16] National Academies of Sciences, Engineering, and Medicine (2023). NCHRP 2023 Annual Report.
[17] Rathje, E., Dawson, C. Padgett, J.E., Pinelli, J.-P., Stanzione, D., Adair, A., Arduino, P., Brandenberg, S.J., Cockerill, T., Dey, C., Esteva, M., Haan, Jr., F.L., Hanlon, M., Kareem, A., Lowes, L., Mock, S., and Mosqueda, G. (2017). "DesignSafe: A New Cyberinfrastructure for Natural Hazards Engineering," ASCE Natural Hazards Review, doi:10.1061/(ASCE)NH.1527-6996.0000246.
[18] SPUR (2023). Home | SPUR. https://www.spur.org, (Accessed February 27, 2023).
[19] Arup. (2013). REDi Rating System: Resilience-Based Earthquake Engineering Design Initiative for Next-Generation Buildings. Arup.
[20] USRC (2023). Home – US Resiliency Council, https://www.usrc.org (Accessed February 27, 2023).
[21] U.S. Government Publishing Office (2023). DCPD-201600045 - Executive Order 13717- Establishing a Federal Earthquake Risk Management Standard, https://www.govinfo.gov/app/details/DCPD-201600045 (Accessed July 7, 2023).
[22] NIST-FEMA (2021). NIST-FEMA Post-Earthquake Functional Recovery Workshop Report, NIST Special Publication 1269, July. https://doi.org/10.6028/NIST.SP.1269
[23] American Society of Civil Engineers (2021). 2021 Report Card for America's Infrastructure – A comprehensive assessment of America's infrastructure, https://infrastructurereportcard.org/ (Accessed April 27, 2023).

Appendix A. Workshop Agenda

The workshop agenda is provided on the following pages.

AGENDA

Workshop on Transportation Systems & Functional Recovery

Host: National Institute of Standards and Technology (NIST)
Date/Time: Wednesday September 28, 2022, 8:30am-5:00pm
Location: National Cybersecurity Center of Excellence (NCCoE)
9700 Great Seneca Highway, Rockville, MD 20850
Contact for Questions: Christine (Zee) Beyzaei (christine.beyzaei@nist.gov)

08:30 - 09:00am **Arrival** and check-in with registration desk

09:00 - 09:10am **Welcome [Jason Averill]**

09:10 - 09:30am **Functional Recovery Overview [Sissy Nikolaou and Zee Beyzaei]**

09:30 - 11:00am **Presentation Block 1***

SCHEDULE	TITLE	PRESENTER
9:30 - 10:00am	Investing in highways' resilience: analyzing the value chain to maximize returns	Dr. Rallis Kourkoulis (Grid Engineers)
10:00 - 10:30am	Resilience of Intermodal Freight Transportation Infrastructure Subjected to Seismic and Hurricane Hazards	Anibal Tafur (Rice University)
10:30 - 11:00am	Recovery models at different resolutions for transportation systems	Dr. Paolo Bocchini (Lehigh University)

**presenters may allow for up to 10 minutes Q&A within their time slot*

11:00 - 11:15am Break *(coffee and refreshments provided)*

11:15 - 12:45pm **Presentation Block 2***

SCHEDULE	TITLE	PRESENTER
11:15 - 11:45am	Advancing Equity in Transportation Data, Models, and Measures	Dr. Tierra Bills (UCLA)
11:45am - 12:15pm	Resilience in Highway Asset Management	Derek Soden (FHWA)
12:15 - 12:45pm	The Nexus between Climate-Smart Transport Infrastructure and Functional Recovery	Guillermo Diaz-Fanas (World Bank)

**presenters may allow for up to 10 minutes Q&A within their time slot*

12:45 - 01:30pm Lunch *(boxed lunch provided)*

01:30 - 01:45pm Overview of Afternoon Breakout Sessions **[Siamak Sattar]**

01:45 - 02:35pm **Breakout Session Block 1**
"Current Status and Challenges"
- Functional Recovery (FR) Framework Development
- Metrics for Quantification and Assessment

(see handout for details)

02:35 - 02:45pm **Report Out**
02:45 - 03:05pm **Discussion**

03:05 - 03:20pm Break *(coffee and refreshments provided)*

03:20 - 04:10pm **Breakout Session Block 2**
"Priorities and Future Vision"
- Models, Tools, and Data
- Implementation and Adoption

(see handout for details)

04:10 - 04:20pm **Report Out**
04:20 - 04:40pm **Discussion**

04:40 - 04:50pm **Closing Remarks [Sissy Nikolaou]**

Please kindly vacate the venue by 5:30pm.

Appendix B. Workshop Attendees

This list includes the workshop participants and organizations represented at the workshop. Names of participants are not included if they declined to have their name published. Five additional individuals registered for the workshop but were not able to attend: four individuals from consulting firms in the private sector, and one individual from a regional transportation agency.

Last Name	First Name	Organization
Averill	Jason	NIST
Beyzaei	Christine	NIST
Bills	Tierra	UCLA
Bocchini	Paolo	Lehigh University
Cheng	Xiaohua	NJDOT
Diaz-Fanas	Guillermo	The World Bank Group
Dukes	Jazalyn	NIST
Johnson	Katherine	NIST
Kourkoulis	Rallis	Grid Engineers
McAllister	Therese	NIST
Nikolaou	Aspasia	NIST
Saadat	Yalda	NIST
Sattar	Siamak	NIST
Soden	Derek	FHWA
Tafur Gutierrez	Anibal	Rice University
Tsatsis	Angelos	Grid Engineers / National Technical University of Athens (NTUA)
Wu	Teng	University at Buffalo

Appendix C. Presentation Abstracts and Abbreviated Presenter Biographies

This appendix contains the presentation abstracts and abbreviated presenter biographies, listed alphabetically by last name.

Tierra Bills

Assistant Professor, UCLA

Dr. Tierra Bills is an Assistant Professor of Civil and Environmental Engineering and Public Policy at UCLA. Dr. Bills specializes in the measurement of transportation system and policy outcomes, and travel demand modeling, with a special emphasis on transportation equity.

Presentation title: "Advancing Equity in Transportation Data, Models, and Measures"

Presentation abstract: This presentation will discuss efforts to advance a framework for equity in Transportation engineering and planning. While the term "equity" has seen renewed attention in recent years, methods and analytical tools for supporting more equitable transportation decisions and outcomes remain underdeveloped. The framework builds on existing travel demand analysis tools and exposes critical gaps in existing data collection, demand modeling, and performance measurement used in the design and planning of transportation systems. This presentation will highlight findings of two recent studies in particular, on data representation of disadvantaged communities and advances in accessibility measurement to include transit service reliability and align with traveler capabilities.

Paolo Bocchini

Professor and Director of Graduate Programs, Department of Civil and Environmental Engineering, Lehigh University

Dr. Bocchini's research lies in the field of computational and probabilistic modeling applied to problems in civil engineering. In particular, his research group focuses on community resilience assessment and enhancement, catastrophe modeling, and life-cycle analysis.

Presentation title: "Recovery models at different resolutions for transportation systems"

Presentation abstract: A recent report of the National Academies recommends that all new investments in transportation infrastructure include an resilience assessment that clarifies costs and benefits for the community of the proposed project. The same report officially links resilience metrics with functionality recovery metrics, thus suggesting that new transportation infrastructure will need accurate recovery models. Strategies for pre-event probabilistic assessment of the seismic recovery profile for bridges and transportation systems are presented and compared, emphasizing their requirements in terms of data and computational resources. Practical tools to perform these analyses are also discussed.

Guillermo Díaz-Fañas (He/Him/His)

Transport Specialist and Unit Climate Focal Point for the Western and Central Africa Region at The World Bank, Washington, D.C.

Guillermo brings over a decade of global engineering and advisory experience in a wide range of infrastructure projects. He currently leads operational financing and analytical transport infrastructure projects in western Africa mainstreaming disaster and climate resilience and mobilizing private sector participation for investments, while strengthening the institutional capacity of client countries as well as their fiscal and regulatory frameworks.

Presentation title: "The Nexus between Climate-Smart Transport Infrastructure and Functional Recovery"

Presentation abstract: Amidst the fight to implement global commitments that promote sustainable development, climate and disaster risk reduction goals have become the central challenge for planning, financing and contract structuring of transportation infrastructure. Preparedness is key for transportation resilience in order to reduce vulnerability, exposure and disaster risk; hence, building capacity at the local and national level becomes imperative to enable an upstream environment that embraces functional recovery. This presentation will highlight ideas to mainstream climate considerations in a multi-hazard environment to enhance the performance of transportation systems. In suggesting such ideas, different frameworks, metrics and tools will be introduced in tandem with operational examples that connect functional recovery with decision-making for planning, engineering and design, and operations and maintenance.

Rallis Kourkoulis

PhD, Aff.M.ASCE; Managing Partner, Grid Engineers

Rallis has 20 years of experience working on infrastructure risk and resilience. He has served as a consultant in numerous multi-hazard risk assessment /mitigation projects in several parts of the world including Europe, the Americas, Africa and the Pacific, while he has been the primary investigator or coordinator of over 20 research projects funded by the EU, NSF, Research Bodies and the industry. He has worked as an expert advisor in the transportation, oil & gas, renewable energy and buildings sectors where he has applied state-of-the art solutions to optimize the resilience of several critical projects.

Presentation title: "Investing in highways' resilience: analyzing the value chain to maximize returns"

Presentation abstract: Following the Bipartisan Infrastructure Law which aims to retrofit infrastructure and speed up economic recovery, it is now more important than ever to offer the tools necessary in order to appraise and optimize such investments from a resilience perspective at a time when many of the country's Infrastructure elements are at a critical state in which their safety - and even their very operability - may be questionable. While several state-of-the-art tools and methodologies to design and build new infrastructure or to retrofit existing ones are available, the prioritization of actions and optimization of spending the allocated budget in a way that targets optimization of functional recovery, and thus contributing to enhancing the nation's resilience, remains a major issue requiring further guidance. Aiming to address these needs, this presentation discusses the development of an online tool aiming to combine existing efforts (by NIST, FEMA and FHWA) into a single resource that will support decisions on how to maximize earthquake resilience of a highway network while optimizing the return on investment.

Derek Soden

Principal Structural Engineer, Federal Highway Administration Office of Bridges and Structures

Derek Soden has been the Principal Structural Engineer in the FHWA Office of Bridges and Structures since 2020. He joined FHWA in 2009 and has also served in the Resource Center and the Division Office for Florida, Puerto Rico, and the Virgin Islands. Prior to joining FHWA, Derek was a bridge design engineer for the Alaska Department of Transportation and Public Facilities (his home state) from 1998 to 2009.

Presentation title: "Resilience in Highway Asset Management"

Presentation abstract: FHWA has a robust program aimed at protecting bridges and tunnels from natural (and human-caused) hazards. This presentation discusses FHWA's current efforts focused on developing frameworks and tools that will allow bridge owners to manage their structural assets in a way that optimizes capital investments while reducing direct (and indirect) costs from closures due to deterioration and extreme events.

Anibal Tafur

Graduate Research Assistant, Rice University

Anibal Tafur is a PhD student working under the supervision of Prof. Jamie Padgett at the Department of Civil and Environmental Engineering, Rice University. His current research focuses on the development of probabilistic methods for risk assessment of infrastructure, specifically resilience modeling of transportation infrastructure subjected to natural hazards, working closely with the NIST Center for Risk-Based Community Resilience Planning.

Presentation title: "Resilience of Intermodal Freight Transportation Infrastructure Subjected to Seismic and Hurricane Hazards"

Presentation abstract: Highway, railway, and port systems constitute the backbone of the US intermodal freight transportation network, and their effective operation is crucial to enabling community resilience after disruptions caused by natural hazards. If regional freight demands are not fulfilled for prolonged periods of time, these disruptions may have serious economic and social consequences. To estimate these effects, it is important to understand how the post-event functionality of these networks' components (roadways, railway tracks, bridges, inland terminals, and port terminals) interact and influence the regional-scale network capacity in terms of transfer of goods. To this purpose, comprehensive frameworks for evaluating intermodal network resilience which integrate critical component-level input are required, although they are lacking in the existing literature. This work presents and discusses frameworks for quantifying the time evolving functionality and resilience of intermodal freight transportation networks subjected to two main natural hazards, namely earthquakes and hurricanes; integrating input datasets and key models, including damage, restoration, network flow, operation, and resource allocation models. By producing estimations of disrupted throughput capacity at regional scales, these frameworks are able to support decision-making by stakeholders involved in transportation resilience, such as private freight operators, government agencies, and transportation researchers; whether planning mitigation measures for existing infrastructure, as well as designing future infrastructure.

Appendix D. List of Reference Materials and Additional Related Resources

This appendix contains a list of reference materials and additional related resources that was provided to workshop attendees as background for the workshop discussions.

List of Reference Materials

(provided as background for the workshop discussions)

1) FEMA P-2090 / NIST SP-1254 (2021): Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time
   a) https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1254.pdf
2) Sattar, S., Cook, D., Johnson, K. (2022): "Preliminary Recovery Categories and Times for a Functional Recovery Framework," Proc. of 12th National Conference on Earthquake Engineering, Salt Lake City, Utah.
   a) Please see Attachment 1.
3) Davis, C.A., Kersting, R., Nikolaou, S., Yu, K. (2022): "Recommendations Toward Functional Recovery Performance of Lifeline Infrastructure Systems," Proc. of San Fernando Earthquake Conference – 50 years of Lifeline Engineering (Lifelines 2021-2022), virtual conference.
   a) Please see Attachment 2.
4) NIST GCR 16-917-39 (2016): Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery
   a) https://nvlpubs.nist.gov/nistpubs/gcr/2016/NIST.GCR.16-917-39.pdf
5) NIST NIST GCR 14-917-33 (2014): Earthquake-Resilient Lifelines: NEHRP Research, Development and Implementation Roadmap
   a) https://nehrp.gov/pdf/nistgcr14-917-33.pdf
6) NIST SP-1269 (2021): NIST-FEMA Post-Earthquake Functional Recovery Workshop Report
   a) https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1269.pdf

Additional Related Resources

1) NIST Community Resilience Planning Guide
   a) https://www.nist.gov/community-resilience/planning-guide
2) NIST Technical Note 2209 (2022): Assessment of Resilience in Codes, Standards, Regulations, and Best Practices for Buildings and Infrastructure Systems
   a) https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2209.pdf
3) National Academies of Sciences, Engineering, and Medicine (2021): Investing in Transportation Resilience: A Framework for Informed Choices
   a) https://doi.org/10.17226/26292

4) SPUR Report (February 2009): Defining Resilience: What San Francisco Needs From Its Seismic Mitigation Policies
   a) https://www.spur.org/sites/default/files/2020-03/SPUR_Defining_Resilience.pdf
5) SPUR Report (February 2009): Lifelines: Upgrading Infrastructure to Enhance San Francisco's Earthquake Resilience
   a) https://www.spur.org/sites/default/files/2013-09/SPUR_Lifelines.pdf