The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Transportation Resilience Metrics

October 19, 2021

@NASEMTRB
#TRBWebinar

Learning Objectives

1. Discuss how transportation agencies are approaching resilience evaluations and investment decisions
2. Describe the multi-step, multi-hazard analytic framework recommended for measuring resilience and informing investment decisions

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

Investing in Transportation Resilience: A Framework for Informed Choices

Dr. Joseph Schofer
Ms. Susanne DesRoches
Dr. Paolo Bocchini

October 19, 2021

Objectives for today's presentations

- To present the study committee's work, with emphasis on
  - How transportation agencies are approaching resilience evaluations and investment decisions,
  - The key approaches research is addressing to measure resilience.
  - The multi-step, multi-hazard analytic framework recommended for measuring resilience and informing investment decisions.
  - Recommendations to Congress and USDOT

Presentation organization

Presentation Topics	Presenting Members of the Study Committee
1. Introduction to the Study	Joseph Schofer (Committee Chair)
2. State of Practice	Susanne DesRoches
3. Review of research literature	Paolo Bocchini
4. Study conclusions and recommendations	Joseph Schofer

Study 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.**

Study Statement of Task

Consideration will be given to

- **types, key features and qualities of metrics that …**
  - can inform investments to increase resilience of transportation system assets …following natural disasters … for a wide array of natural hazards such as hurricanes, floods, wildfires, heat waves, high winds, and changing freeze-thaw patterns.
- the **kinds of data, methods, and analytic tools needed …**
  - to design and apply such metrics.
- metrics from the literature and in use, developed, or recommended by federal agencies, state, tribal, and local governments, metropolitan planning organizations, and other public and private transportation practitioners.

Study Statement of Task

Based on the findings, the committee will **make recommendations… 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.
- Give special attention to metrics that can be applied by Congress and other policymakers to inform decisions about when and how much to invest in transportation resilience, and how to design infrastructure funding programs that prioritize resilience.

Committee's Approach

- Adopted a broad definition of natural hazards, to include
  - significant acute weather and geophysical disturbances (e.g., hurricanes, earthquakes), and
  - longer-term (chronic) stressors (e.g., sea level rise, changing temperature and precipitation norms), some exacerbated by climate change.
- Adopted definition of resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption."
- Adopted multimodal perspective, freight, passenger, private and public.
- Considered both the research and the state of the practice.

State of Practice
Case studies

Introduction

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
- Some have developed **indicators** that allow them to track progress in improving the level of transportation system resilience over time.
- Some 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.

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.

These include analysis methods and metrics for

- **likelihood** of natural hazard events
- **vulnerability** of the infrastructure or transportation system to damage or disruption
- **consequences** of a particular level of damage or disruption, which are often expressed as a combination of owner costs and user costs; and
- **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

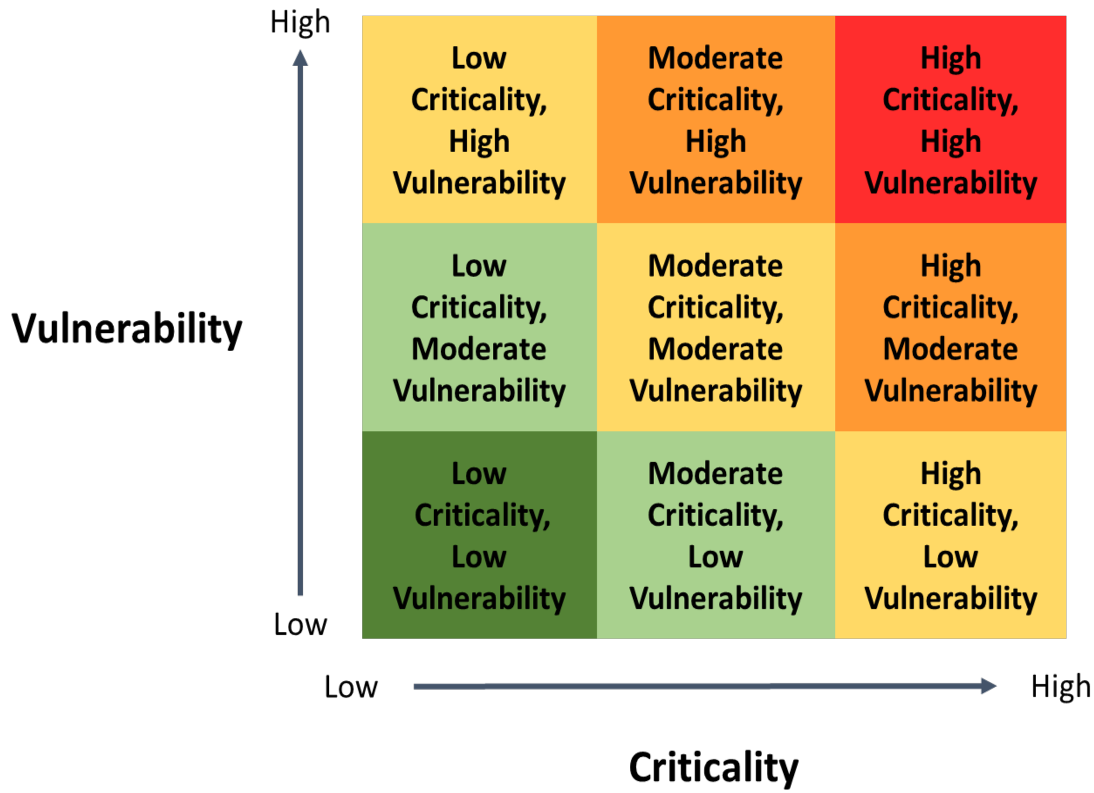
– Metrics used in practice – Examples

Resilience Product	Input Data and Computed Metrics
Risk value - expected disruptions cost (Utah DOT)	Hazard types and probabilities, asset vulnerability, owner and user disruption costs, criticality(traffic volumes, network redundancy)
Annual asset risk (Colorado DOT)	Hazard types and probabilities, asset vulnerability, criticality (traffic, freight volumes, tourism, social vulnerability, network redundancy), diversion costs, worst-reasonable case, benefit-cost analysis
Resilience indicator score (LACMTA)	Hazard types, asset condition and vulnerability, network redundancy, agency preparedness, financial resources, staffing, communications resources
Asset vulnerability profiles (San Diego Airport)	Hazard types (flooding, heat extremes) and future event scenarios, inventory of exposed assets, criticality (aircraft operation volumes), asset replacement costs
Risk-based resilience design guidelines (New York City, Port of Long Beach	Hazard types and probabilities, asset criticality, service life, disruption costs, replacement costs

— Metrics used in practice — Criticality and vulnerability matrix

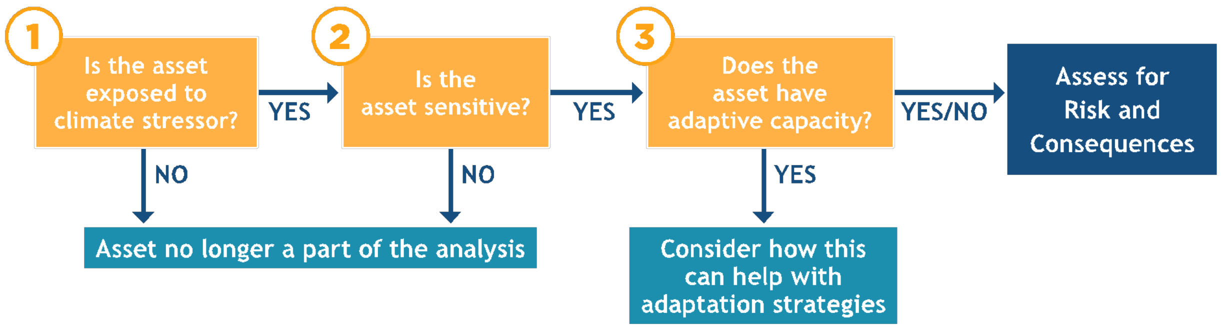
There is an emerging practice of defining the need for resilience using the intersection of vulnerability and criticality

or of risk and criticality.



Vulnerability Assessment Case Study, San Diego International Airport (FAA pilot)

- Vulnerability assessment followed the pattern laid out in FHWA's VAST



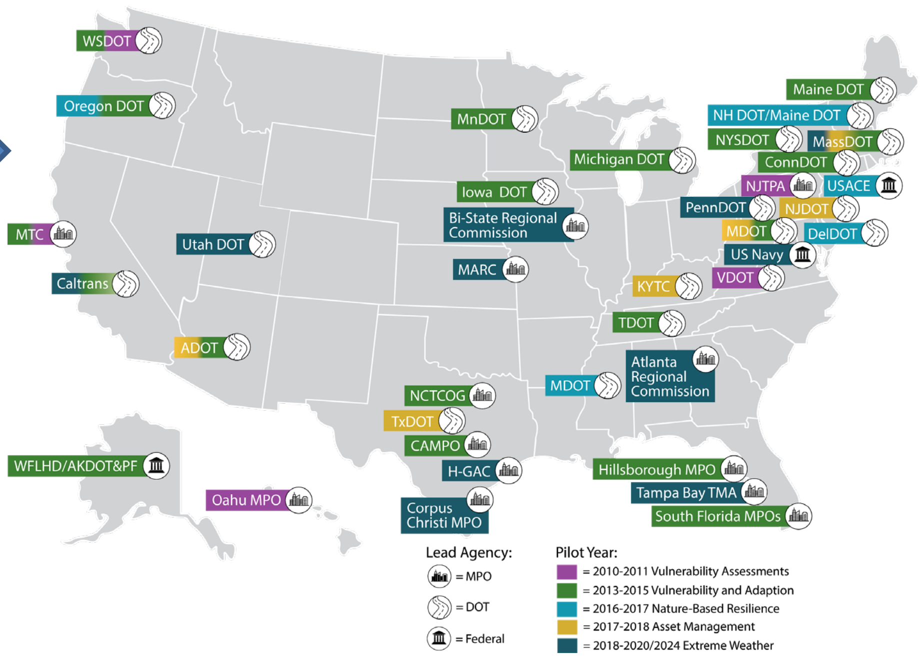
- Analysis of sensitivity and adaptive capacity yielded important information.
  - Example of factors that influenced sensitivity: the presence of electrical equipment.
  - Example of factors that influenced adaptive capacity: the ability to elevate or relocate assets.
- However, **analysis of exposure turned out to be the most important** of the three for assessing vulnerability

— Testing and Improvements — Federal Pilot Programs

Have provided significant means of advancing the practice of resilience planning and decision making among transportation agencies

Pilot projects funded by

- Federal Highway Administration (FHWA)
- Federal Transit Administration (FTA)
- Federal Aviation Administration (FAA)
- Office of the Secretary



Summary of Metrics

Output Measures

- Annual Risk (Colorado DOT)

Intermediate Measures

- Hazard Probability
- Vulnerability Consequences

Input Data

- Probability of rockfalls
- Probability of floods
- Probability of debris flows
- Engineering judgement
- Repair costs to CDOT
- Number of days highway closed
- Length of detour required
- Lost wages and truck revenues

See Table 3-3 in report for summary of these as applied by various agencies

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Review of Research on Resilience Metrics

How we quantify resilience

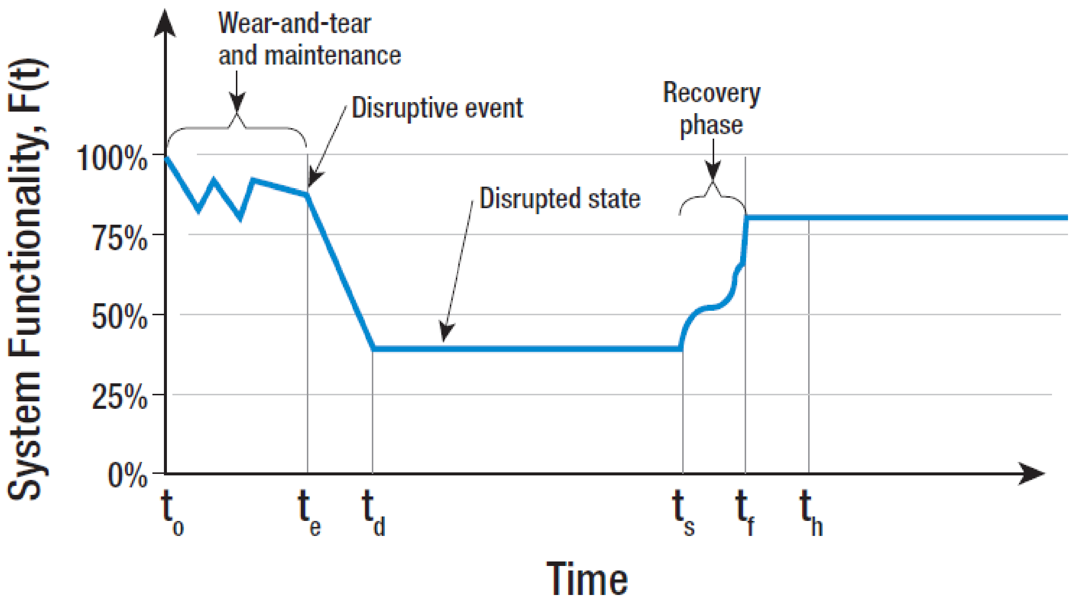
The concept of **resilience**

is rooted in the concept of

“**functionality**” (or performance, level of service)

and focuses on the post-disruption recovery phase

How research describes post-disruption functionality

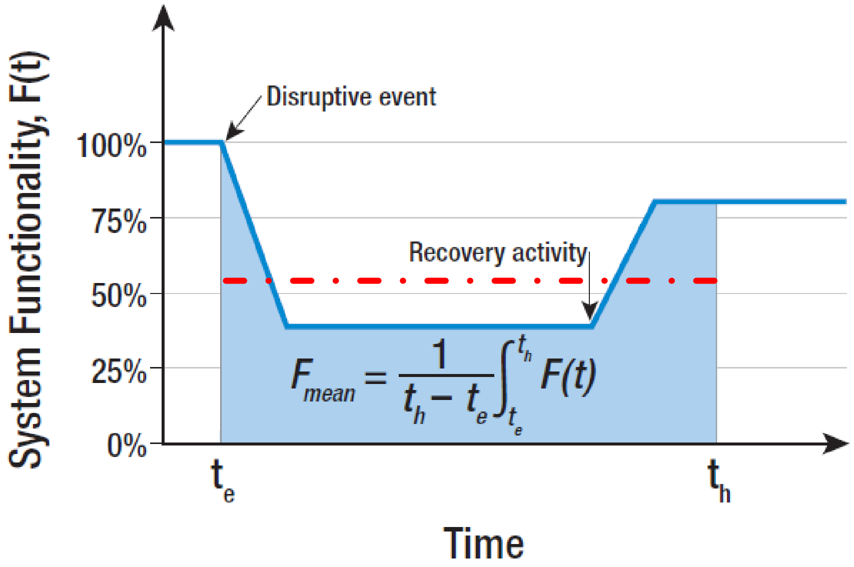


Recovery curves describe the evolution of functionality over time.

They can be applied almost to any system and any perturbation. E.g.,

- Performance of various modes of transportation under natural hazards
- % of power demand satisfied by a utility company after a hurricane
- % of lanes open for a bridge

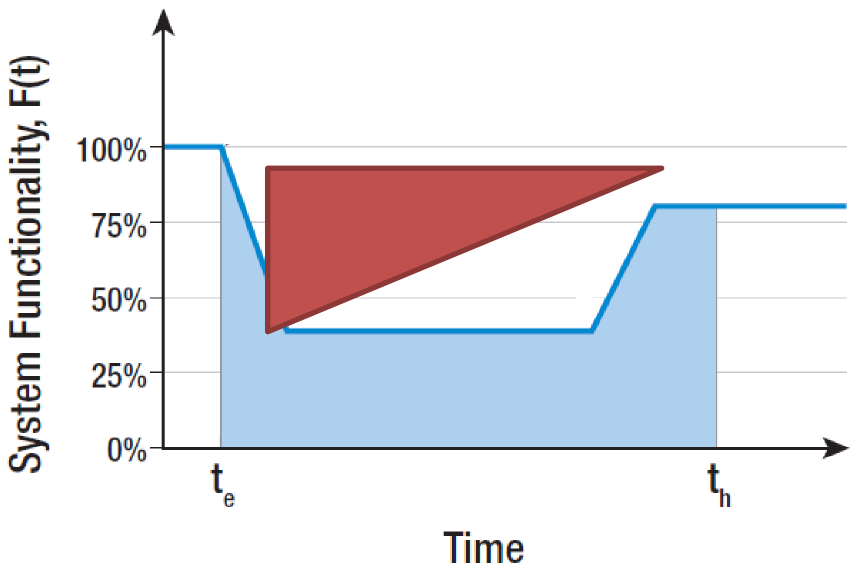
Resilience metrics based on recovery curves



Examples

- “Resilience index” is the mean value of functionality after the perturbation from the disruptive event

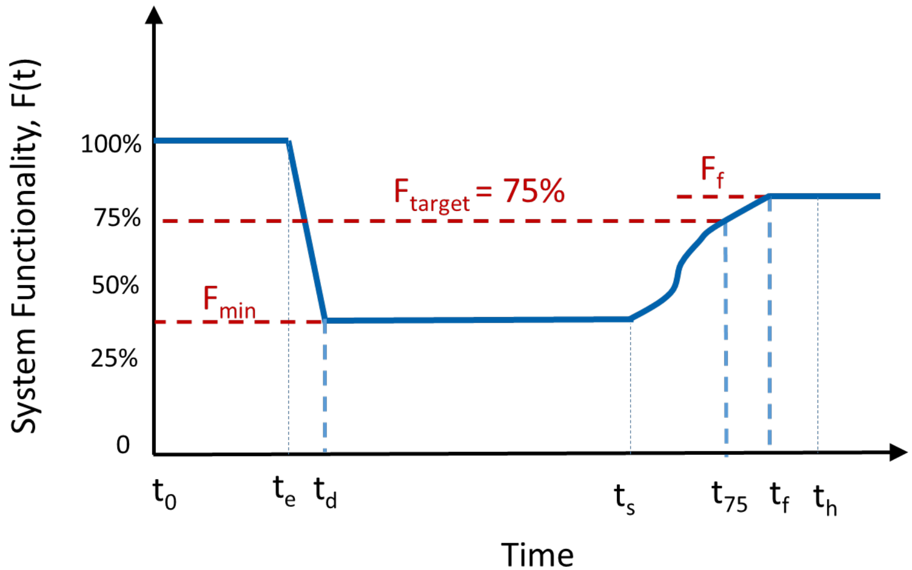
Resilience metrics based on recovery curves



Examples

- "Resilience index" is the mean value of functionality after the perturbation from the disruptive event
- Resilience Triangle

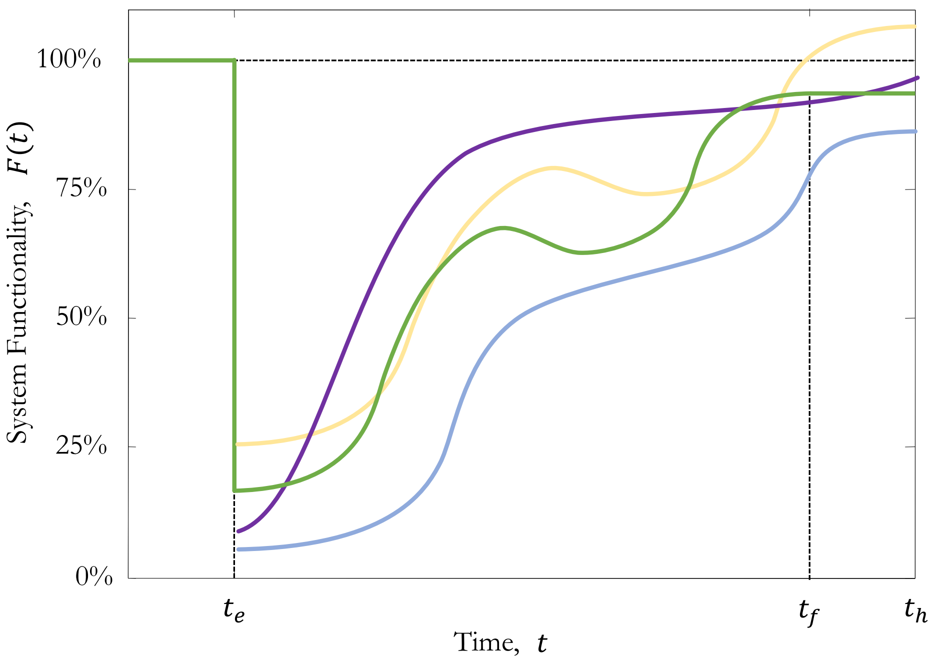
Resilience metrics based on recovery curves



Examples

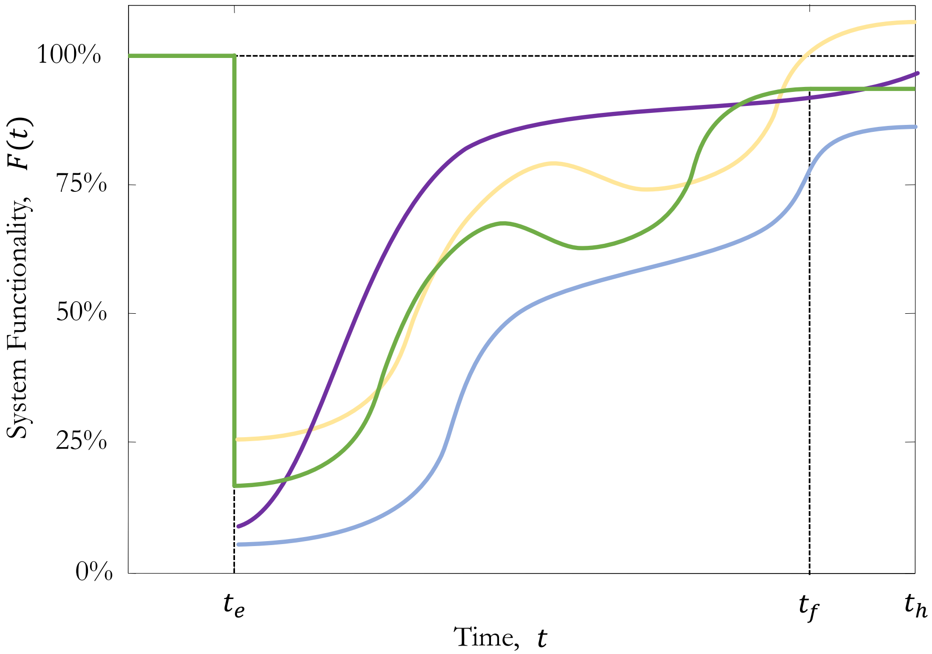
- "Resilience index" is the mean value of functionality after the perturbation from the disruptive event
- Resilience Triangle
- Time to reach a target level of functionality (F_{target})
- Minimum level of functionality at any time during recovery (F_{min})
- Level of functionality restored at the end of the recovery (F_f)

Accounting for uncertainties



- In pre-event studies, we have to account for the fact that the functionality recovery curve is subject to considerable uncertainty
- Examples or sources of uncertainty:
  - Extent of physical damage
  - Availability of personnel and resources for the recovery
  - Functionality of other systems on which transportation relies for recovery or for its own functionality
  - Weather and recovery tasks duration

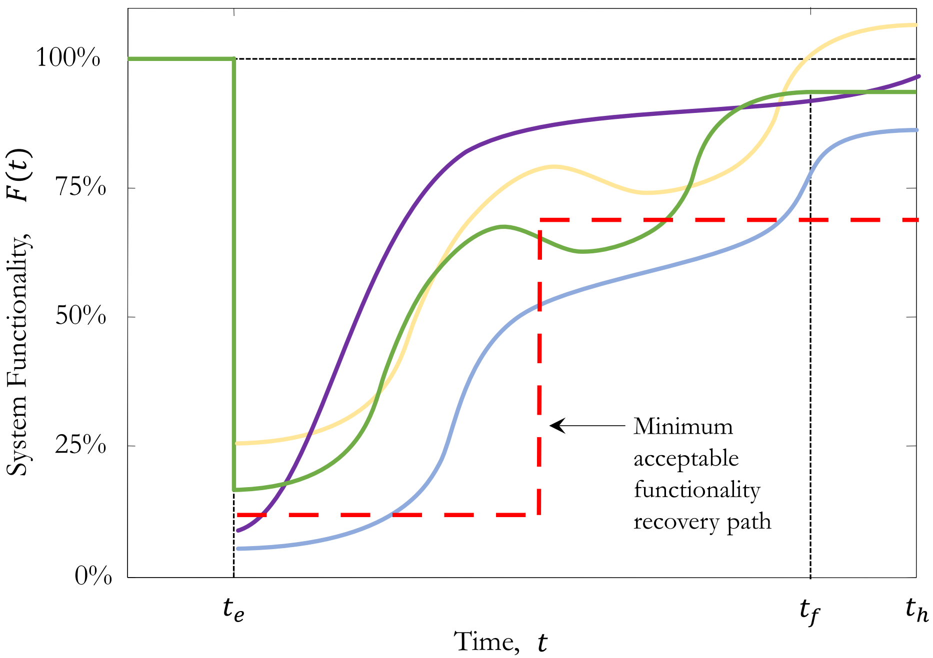
Accounting for uncertainties



Examples of probabilistic metrics

- Mean recovery curve or mean resilience index (simple, but not so informative)

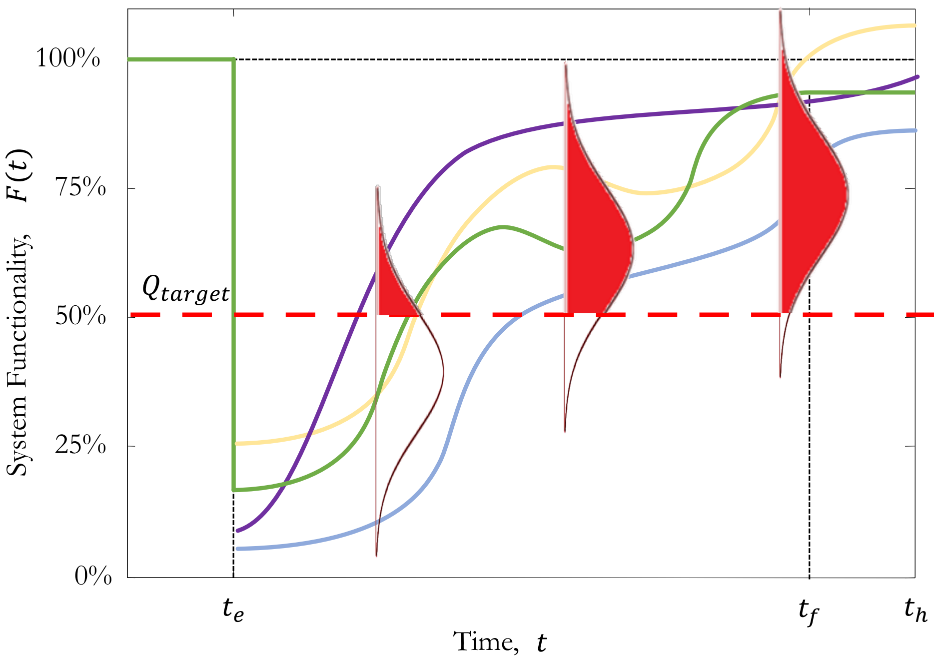
Accounting for uncertainties



Examples of probabilistic metrics

- Mean recovery curve or mean resilience index (simple, but not so informative)
- Probability of acceptable recovery i.e., count how many recovery curves stay always above the minimum recovery (focus on tails)

Accounting for uncertainties



Examples of probabilistic metrics

- Mean recovery curve or mean resilience index (simple, but not so informative)
- Probability of acceptable recovery i.e., count how many recovery curves stay always above the minimum recovery (focus on tails)
- Probability of exceeding a target level of functionality (focus on variance or tails)

Context for the use of these metrics

- Select one or more scenarios with appropriate strategy (better more than one)

- Select one or more **performance metrics**
- For each scenario, predict performance recovery curve (with appropriate tools)

- Select one or more **resilience metrics**
- For each scenario and each performance metric, compute resilience metrics

Conclusions and Recommendations

Committee's Observations

- Research
  - strong theoretical base;
  - largely focused on models and measures of recovery from disasters;
  - translation to practice requires additional research, particularly predictive models to assess effectiveness of investments in resilience.
- Practice
  - considerable progress in practice focused on supporting management and investment decisions; this includes important supporting concepts and measures of vulnerability and criticality.
- The committee worked to build connections between the two
  - Goal: making recommendations about advancing the practice.

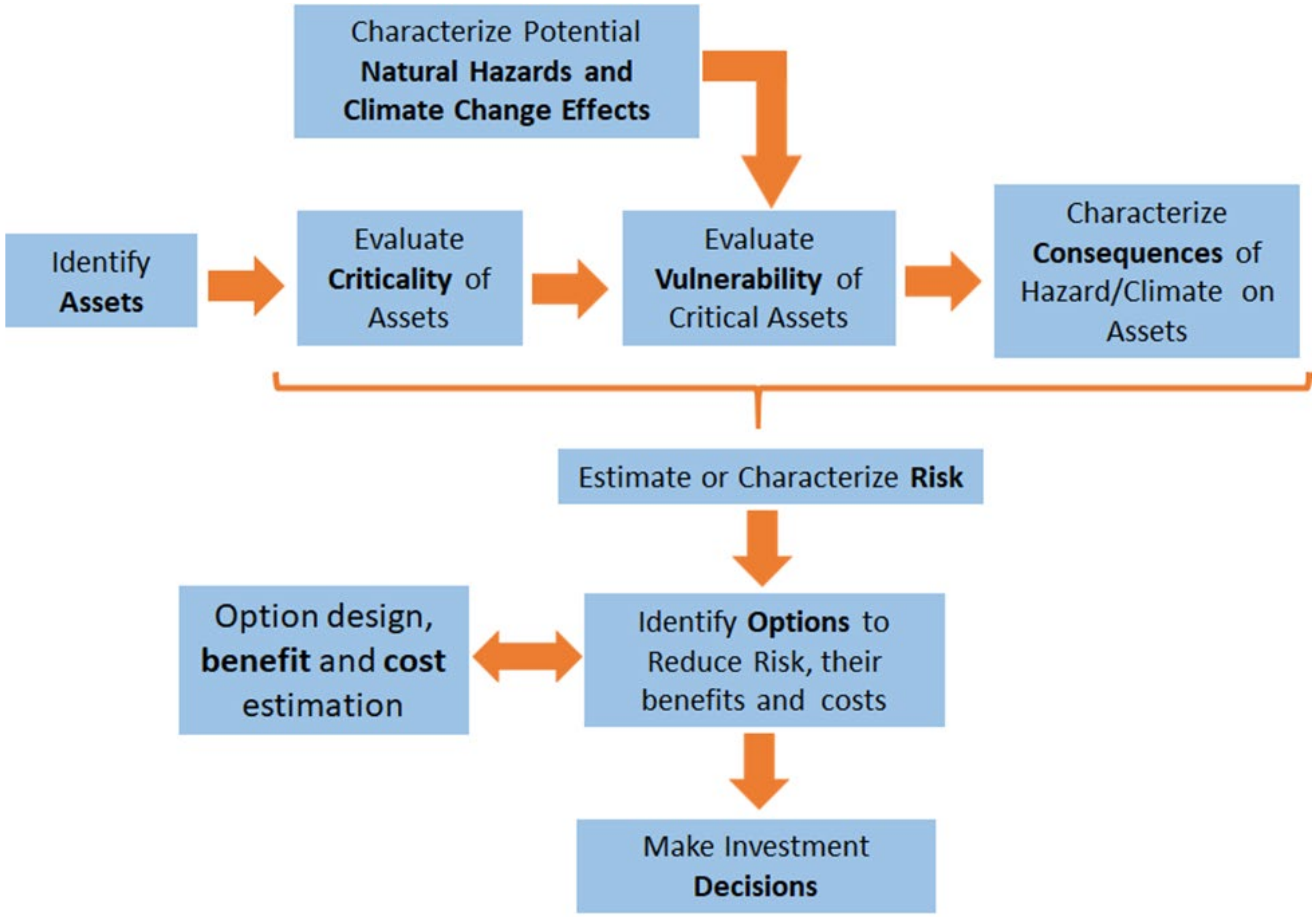
Committee's Observations

- A single resilience metric is unlikely to be found.
- Reasons:
  - Transportation systems comprise a broad range of infrastructure types, scales, ownership and management patterns;
  - Complex combination of infrastructure, processes, and people determine resilience and response to disaster; and
  - Transportation faces a wide rage of threats from natural hazards, demands for services, demographic and environmental conditions that together determine resilience.

Committee's Conclusions

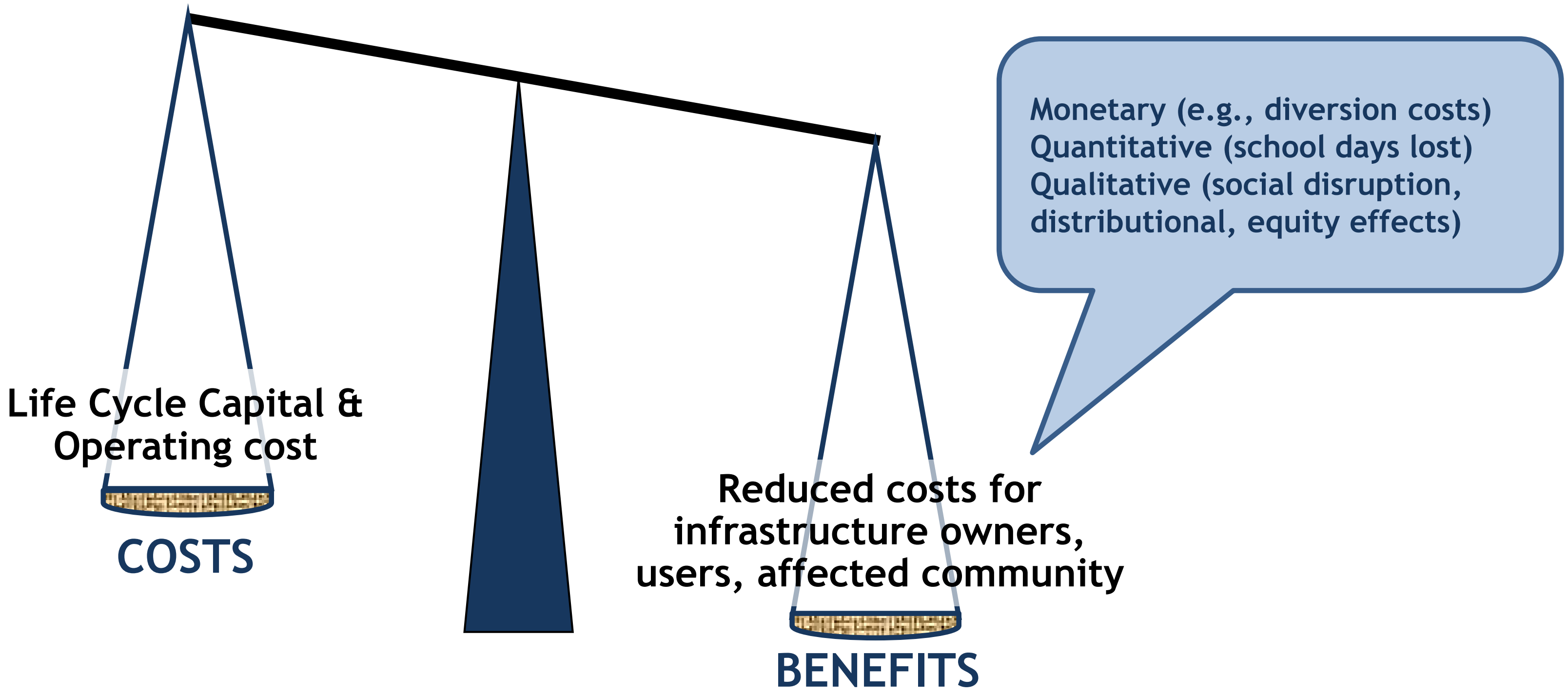
- For decision-support analysis, there is a need for a collection of metrics, and
- Analyses that use appropriate metrics within a strong decision support framework can help make the case for investments in resilience.

The principal product of this report is a
<u>framework for assessing benefits of resilience investments</u> 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.



BCA Evaluation Framework

Explicit identification, comparison of benefits, costs



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 the prospect of changes in the risk of natural hazards and new environmental conditions stemming from climate change.

Recommendation 2

The Office of the Secretary of Transportation (OST) should promote the use of benefit-cost analysis (BCA) 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.

Recommendation 3

OST should provide guidance to the USDOT 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 upon lessons learned from initiatives by the FHWA and other federal and state agencies to pilot analytic approaches like the multistep framework recommended above for use in assessing resilience on major transportation projects eligible for federal funds.

Recommendation 4

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

Recommendation 5

OST 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 multistep analytic framework.

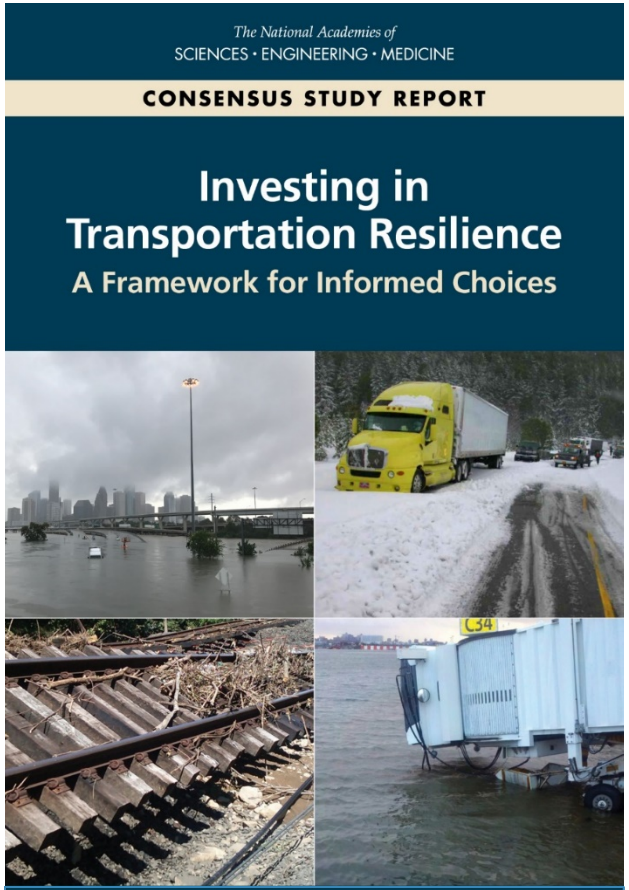
Bottom Line

- Investing in the resilience of our transportation system is essential as threats from natural hazards and climate change grow and the systems themselves age. (But) Making those investments is complex and uncertain...
- As a result, there is no simple solution and **no singular metric of resilience.**
- Because both natural hazards faced by transportation systems and the systems and their functions are in a continuous state of flux, while a variety of transportation investments are made all the time, it is important to assure that resilience is considered throughout the life of systems. Key aspect:
  - Use of an analytic framework that includes
    - detailed asset inventories;
    - assessments of future natural hazards;
    - identification of critical assets, and
    - predictions of vulnerability of the assets from possible hazards
  - Apply Benefit-Cost Analysis to evaluate options.
- Sufficient and updated data sources are vital.

Thank you for your attention

Committee

- **Joseph Schofer,** *Northwestern University*
- **Paolo Bocchini,** *Lehigh University*
- **Henry Burton,** *University of California*
- **Susanne DesRoches,** *New York City Mayor's Office*
- **Alexander Heil,** *Citizens Budget Commission*
- **Geraldine Knatz (NAE),** *University of Southern California*
- **Elise Miller-Hooks,** *George Mason University*
- **RADM Ann Phillips, (U.S. Navy, retired),** *Office of the Governor, Commonwealth of Virginia*
- **José Ramírez Márquez,** *Stevens Institute of Technology*
- **Víctor Rivas,** *Jacobs Engineering Inc.*
- **John ("Jack") Wells,** *Retired Transportation Economist*
- **Shawn Wilson,** *Louisiana Department of Transportation and Development*



Link to report:
https://www.nap.edu/catalog/26292/investing-in-transportation-resilience-a-framework-for-informed-choices

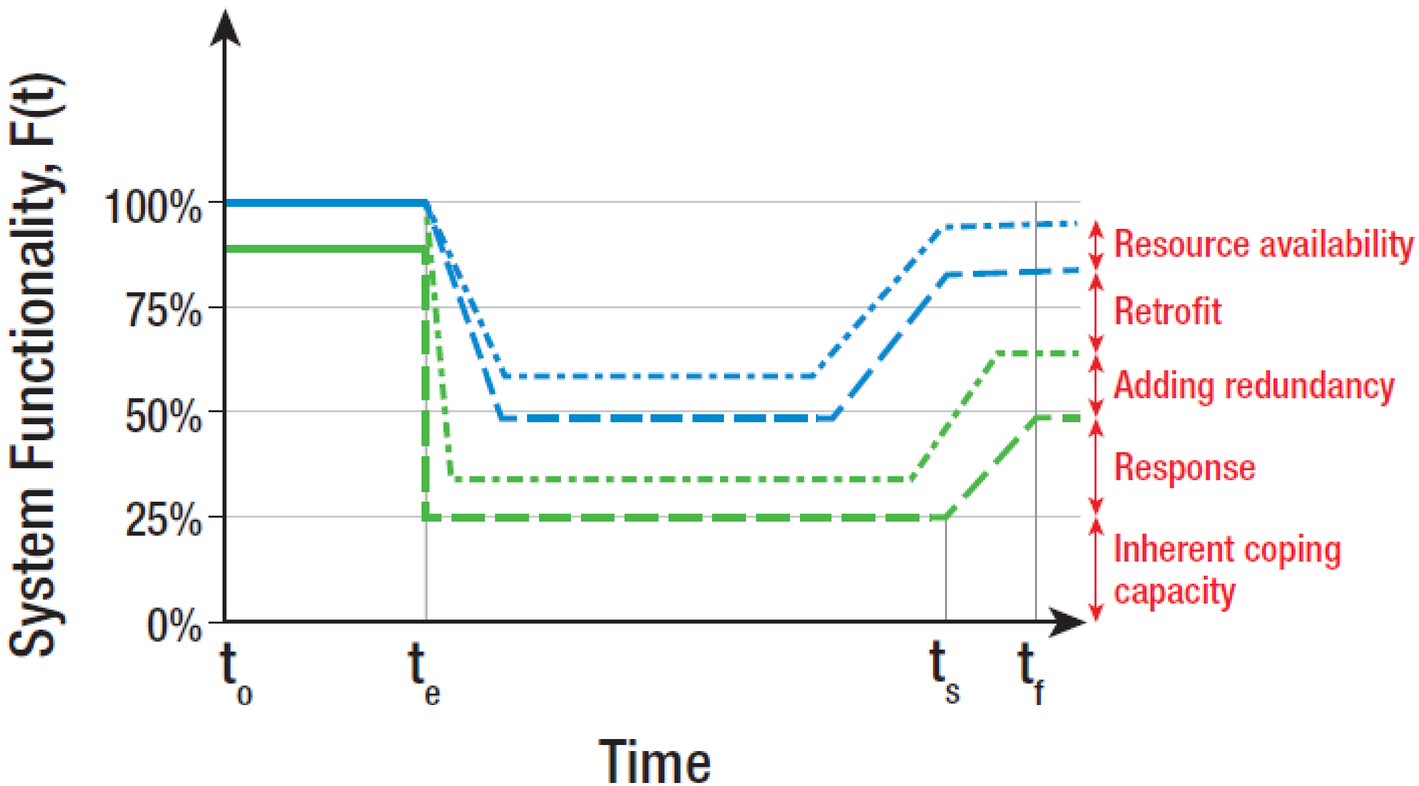
Recommendation Summary & Discussion

1. Consider requirement that all projects eligible for federal funding that involve long-lived assets undergo well-defined resilience assessments.
2. Promote use of BCA to guide decisions.
3. Provide guidance to DOT modal administrations on the development of analytic methods and tools for estimating resilience benefits.
4. Assure the viability and timeliness of data necessary to make informed resilience investment decisions by studying (a) required data types, (b) data sources, and (c) means for making the data more suitable to this purpose.
5. Design and conduct structured pilots across modes.

Key Definitions

- ***Resilience***—The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption.
- ***Natural hazard***—A natural phenomenon that can produce damaging disruptions on systems and their functionality.
- ***Climate change***—Changes in average weather conditions that persist over multiple decades or longer.
- ***Disruption***—Degradation of system functionality due to a hazard.
- ***Exposure***—Whether an asset experiences a stressor.
- ***Risk***—The potential for loss of functionality of a system from exposure to a hazard that exploits its vulnerability.

Contribution to resilience from different actions



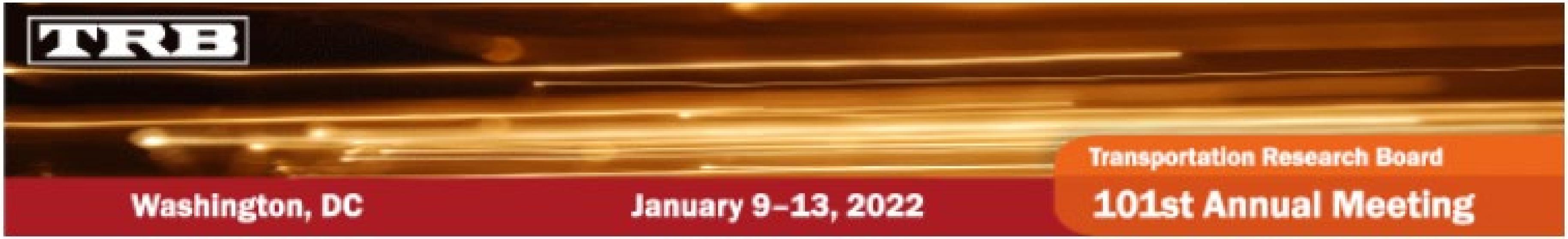
Today's Panelists

Moderator: Joseph Schofer,
Northwestern University

Susanne DesRoches,
New York City Mayor's Office

Paolo Bocchini,
Lehigh University

Register for TRB's Annual Meeting!



Register now for our January meeting! ***There will be no onsite registration this year.***

#TRBAM

The National Academies of
SCIENCES · ENGINEERING · MEDICINE
TRB
TRANSPORTATION RESEARCH BOARD

TRB Weekly

TRB Weekly covers the latest in transportation research.

- Subscribe to the newsletter for the most recent TRB news & research!

https://bit.ly/ResubscribeTRBWeekly

TRB’s Podcast!

- Have you heard that we have a podcast, TRB’s Transportation Explorers?
- Listen on our website or subscribe wherever you listen to podcasts!

#TRBExplorers

Get involved with TRB

- Receive emails about upcoming webinars:

https://mailchi.mp/nas.edu/trbwebinars

- Find upcoming conferences:
  http://www.trb.org/Calendar

@NASEMTRB
@NASEMTRB
Transportation Research Board

#TRBWebinars

Get Involved with TRB

#TRBwebinar

@NASEMTRB

@NASEMTRB

Transportation Research Board

Getting involved is free!

Be a Friend of a Committee bit.ly/TRBcommittees

– Networking opportunities

– May provide a path to Standing Committee membership

Join a Standing Committee bit.ly/TRBstandingcommittee

Work with CRP https://bit.ly/TRB-crp

Update your information www.mytrb.org