Improving Transportation Infrastructure Resilience through Post-event Damage Inspection (PDI) and Post-event Engineering Investigation (PEI)

FHWA-HIF-24-042
Office of Infrastructure

U.S. Department of Transportation
Federal Highway Administration


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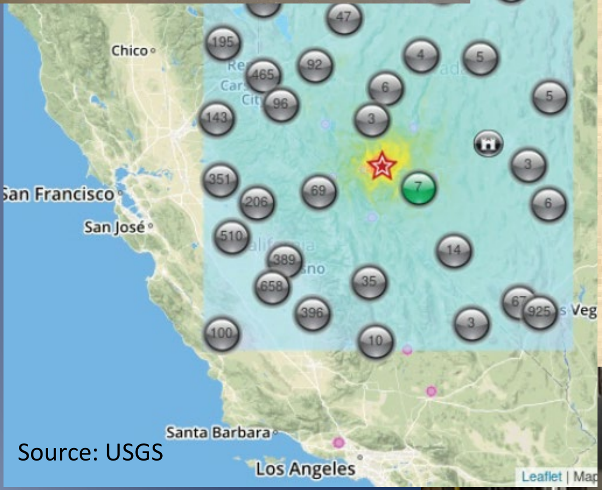

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HIF-24-042	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Improving Transportation Infrastructure Resilience through Post-event Damage Inspection (PDI) and Post-event Engineering Investigation (PEI)	5. Report Date June 2024
	6. Performing Organization Code:
7. Author(s) Rallis Kourkoulis, PhD, Fani Gelagoti, PhD, Mabel Chedid, PhD, Maria Antoniou, Antonios E. Alvertos, Sissy Nikolaou, PhD, PE and C. Jeremy Hung, PE.	8. Performing Organization Report No.
9. Performing Organization Name and Address WSP USA Inc. 1015 Half Street SE Suite 650 Washington DC, 20003	10. Work Unit No.
	11. Contract or Grant No. DTFH6114D00048/693JJ319F000254
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration, Washington, DC 20590	13. Type of Report and Period
	14. Sponsoring Agency Code

15. Supplementary Notes

FHWA COR:

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Contractor Project Manager: C. Jeremy Hung, P.E.

16. Abstract

This document summarizes the highway infrastructure resilience framework and practices for Post-Event Damage Inspection (PDI) and Post-Event Engineering Investigation (PEI) developed under the FHWA Task Order "Framework for Infrastructure Resilience and Post-Hazard Response." The document describes the framework components: pillars, lenses, dimensions and indicators. It outlines the steps suggested for the evaluation of the resilience of highway infrastructure and presents a Resilience Evaluation Tool incorporating these steps. The application of the Resilience Evaluation Tool is illustrated using a demonstration test case. This document also presents an enhanced methodology for PDI and addresses the needs and gaps identified in the current procedures for pre-event planning, post-event inspection, team composition, and team training. In addition, this document suggests an enhanced PEI methodology covering field reconnaissance missions, data collection, processing, and interpretation methods, post-event network-level rehabilitation, and long-term resilience building strategies. The evaluation of highway infrastructure resilience following the resilience framework presented herein is contingent on the completeness and quality of the resilience database. For this reason, the document provides suggestions on the data categories and data collection phases and methods to support building a comprehensive database for resilience, comprising damage and non-damage data relevant to the network performance assessment ex-ante and ex-post disaster events.

17. Key Words	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 96	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Acronyms and Abbreviations

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
AASHTOWare™ BrM	American Association of State Highway and Transportation Officials Software for Bridge Management
ASCE	American Society of Civil Engineers
Caltrans	California Department of Transportation
CAPEX	Capital Expenditures
CC	Communication/Press Coordinator
CDL	Characteristic Damage Level
CPT	Cone Penetration Test
DCPT	Dynamic Cone Penetration Test
DDA	Detailed Damage Assessment
EARR	Early Access Reconnaissance Report
EDC	Emergency Data Coordinator
EERI	Earthquake Engineering Research Institute
EMC	Emergency Management Coordinator
ERT	Emergency Response Team
ENS	USGS Earthquake Notification Alert
ERP	Emergency Response Plan
FAT	Field Assessment Team
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FR	Fast Reconnaissance
FRC	Fast Reconnaissance Coordinator
GEER	Geotechnical Extreme Events Reconnaissance
GIS	Geographic Information System
GPS	Global Positioning System
HAZUS-MH	FEMA Hazards US Multi-hazard
InSAR	Interferometric Synthetic Aperture Radar
IoT	Internet of Things
IT	Information Technology
LE	Loss Estimates
LFE	EERI Learning from Earthquake(s)
LiDAR	Light Detection and Ranging
MASW	Multichannel analysis of surface waves
ME	Managing Engineer
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration

NTI	National Tunnel Inventory
PDA	Preliminary Damage Assessment
PDAR	Preliminary Damage Assessment Responder
PDI	Post-event Damage Inspection
PDE	Pre-Disaster Evaluation
PEI	Post-Event Engineering Investigation
PEIC	PEI Champion
PEQIT	Post-Earthquake Investigation Team
PGA	Peak Ground Acceleration
PGV	Permanent Ground Velocity
PPE	Personal Protective Equipment
RADAR	Radio Detection and Ranging
RET	Resilience Evaluation Tool
REDARS 2™	Risks from Earthquake Damage to Roadway Systems (a tool developed for FHWA)
RTC	Reconnaissance Team Coordinator
SA [T]	Spectral Acceleration at T period. In case only 'SA' is used, the Spectral Acceleration at the natural period of the system is meant.
SA(T_1)	Spectral Acceleration at the Fundamental Period of the Ground Shaking Record
SASW	Spectral Analysis of Surface Waves
ShakeCast	USGS ShakeMap Broadcast
SHM	Structural Health Monitoring
SME	Subject Matter Expert
SONAR	Sound Navigation and Ranging
StEER	Structural Extreme Events Reconnaissance
TOMIE	FHWA Tunnel Operations, Maintenance, Inspection, and Evaluation
TOSE	Technical, Organizational, Social, and Economic
TV	Total Value (often refers to portfolio of transportation structures)
UAS	Unmanned Aircraft System
USGS	United States Geological Survey
VAST	FHWA Vulnerability Assessment Scoring Tool

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Chapter 1 Introduction

The Federal Highway Administration (FHWA) initiated a study to examine potential approaches for the following:

(A) A holistic approach to support highway infrastructure resilience that not only addresses the design needs in withstanding extreme events, but also offers adequate support to planning for and responding to disasters.

(B) Highway infrastructure resilience framework to evaluate the resilience of bridges and tunnels against extreme events and identify resilience improvements from various infrastructure investments.

(C) Suggestions for Post-Event Damage Inspection (PDI) procedure.

(D) Suggestions for Post-Event Engineering Investigation (PEI) procedure.

(E) A framework for resilience data collection to serve as the foundation for the resilience evaluation and informed decision-making.

This final report summarizes the work accomplished in the study and presents the framework and practices.

As noted in Executive Order 14008: Tackling the Climate Crisis at Home and Abroad, the United States and the world face a profound climate crisis. We have a narrow moment to pursue action at home and abroad in order to avoid the most catastrophic impacts of that crisis and to seize the opportunity that tackling climate change presents[1]. State Departments of Transportation (State DOTs) identify risks that can affect the condition and the performance of the National Highway System pavements and bridges, including risks associated with current and future environmental conditions, such as extreme weather events, climate change, seismic activity, and risks related to recurring damage and costs (23 CFR 515.7(c)(1)). The mitigation approaches should be adaptive and built on data-driven strategies that generate and make use of relevant field data.

The Nation's transportation system is essential to the economic prosperity and quality of life of communities. In order to play this critical role, infrastructure must be secure and resilient to a myriad of hazards[2]. The Bipartisan Infrastructure Law (BIL)[3] makes historic investments to improve the resilience of transportation infrastructure, helping States and communities prepare for hazards such as wildfires, floods, storms, and droughts exacerbated by climate change.[4]

Under 23 U.S.C. 101(a)(24) “resilience,” with respect to a project, is defined as “a project with the ability to anticipate, prepare for, or adapt to conditions or withstand, respond to, or recover rapidly from disruptions, including the ability: (A) (i) to resist hazards or withstand impacts from weather events and natural disasters; or (ii) to reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters.”[5] In this report, the capability of achieving greater multi-hazard resilience of roadway systems including bridges

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[1] Executive Order 14008, 2021, https://www.govinfo.gov/content/pkg/FR-2021-02-01/pdf/2021-02177.pdf

[2] FHWA, 2017, https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/ratp/index.cfm

[3] Enacted as the Infrastructure Investment and Jobs Act (IIJA), Pub. L. No. 117-58 (Nov. 15, 2021).

[4] FHWA, 2022, https://www.fhwa.dot.gov/environment/sustainability/resilience/policy_and_guidance/protect_formula.pdf

[5] See also FHWA Order 5520 (providing FHWA definition of resilience prior to enactment of BIL).

and tunnels asset classes and their subgroups, is attributed to (A) owners'/managers' ability to anticipate and prepare, and (B) the built components' ability to absorb, adapt, and rapidly recover.

Quantifying resilience serves many purposes, including:

(A) The evaluation of the effectiveness of resilience investments.

(B) The communication of resilience investment outcomes with the public and decision-makers.

(C) The prioritization of resilience enhancement strategies.

As reflected in the definition, resilience depends on many factors; therefore, its direct measurement as the aggregate of reduction in services and intervention costs may not be presently feasible. The quantification of service reduction and associated life cycle cost needs probabilistic hazard intensity, probabilistic damage functions, probabilistic consequence models, and an efficient computation scheme to integrate. Such calculations heavily depend on the devastating consequences of rare events, including cascading effects, for which obtaining case data, lab evidence, and analytical results is a long and expensive process. While many of such works are ongoing, an interim solution may be needed to approximate the resilience improvement from intervention. The framework suggested by this study approaches resilience evaluation by breaking it down into different categories at successive steps until reaching quantifiable indicators that capture the factors relevant to highway infrastructure systems. Chapter 2 of this report outlines the suggested steps and components of the resilience evaluation framework that are incorporated in the "Resilience Evaluation Tool." An application of this tool using a demonstration test case is presented in chapter 6.

Rapid response in the form of post-event damage inspections (PDIs) is important in evaluating the performance of the assets and making decisions for immediate measures that aim at minimizing interruption of services while ensuring public safety. PDI procedure documents from State DOTs, Federal organizations, and research institutes were reviewed to identify the needs and gaps within the state-of-practice of PDI procedures, protocols, and emergency response plans. Chapter 3 presents an enhanced PDI methodology addressing the needs identified in the current procedures for pre-event planning, post-event inspection, team composition, and team training. At the planning and preparation stage, agencies should anticipate, and train for potential hazard scenarios to successfully identify, plan, and efficiently coordinate the response. Proactive planning can lead to expedited disaster response and significant cost reduction. For example, lead agencies could establish methodologies/procedures to assist prioritization of post-disaster asset inspections and invest in digital infrastructure and disaster-related data management. It could be beneficial for lead agencies to rely less on visual inspections and manual data collection and more on technology-based procedures. To this end, the report discusses the importance of standardization in data collection protocols, the use of mobile applications in PDI reporting procedures, and the potential benefit of clear intra- and inter-agency communication protocols (describing roles and contributions) and supporting training activities.

Post-event engineering investigations (PEIs) should be conducted in an organized and impartial manner to document the performance of highway infrastructure systems and their asset classes in the aftermath of disasters. The focus should not only be on failure cases but also on success cases. The latter can be useful for the updating of predictive computational models and revision of existing design practices. PEI practices also include reporting and disseminating lessons learned from the extreme event to multiple stakeholders. Such practices can lead to highlighting the needs and gaps in existing design approaches, as well as construction codes and specifications. While several U.S. States have PDI procedures in place, current PEI endeavors are largely focused on ad hoc reconnaissance missions mainly performed by nonprofit organizations and research institutions. As a result, PEI procedures are not consistent or organized in a way that can generate well-documented case histories. There is currently a loose connection between the learnings from PEI missions and the enhancement of the resilience of a highway network.

Chapter 4 of this report discusses how the scope of PEI efforts can be enhanced to improve highway infrastructure resilience. This chapter presents suggestions on the procedures that cover field reconnaissance missions, data collection, processing, and interpretation methods, post-event network-level rehabilitation, and long-term resilience-building strategies. The suggestions include the development of robust reconnaissance frameworks with detailed procedures for all hazards on a Federal or State level, and the use of emerging technologies for data collection and digital data reporting. The suggested procedure identifies the need for setting data collection objectives during field missions. Such objectives would help ensure a certain level of coherence among reconnaissance reports. To enhance post-event network rehabilitation, accelerated reconstruction practices are discussed. These practices can span from pre-engineered solutions per damage/hazard, to contract management and flexibility in the design based on the availability of materials. The importance of efficient repair prioritization strategies in decreasing the network recovery time is also highlighted. State-of-the-art practices are presented for data processing, interpretation, and storage, including well-designed electronic archival systems and the deployment of Big Data platforms to act as disaster summary databases. Furthermore, chapter 4 discusses how PEI data may be integrated into the resilience plan of lead agencies to support long-term investment decisions. Core to the suggested procedure is the assessment of network vulnerability and the establishment of a prioritization procedure tailored to the specific resilience objectives of the State DOT. The procedure may also benefit from a systematic and standardized lifecycle monitoring of critical highway assets to update structural data and other model parameters and validate ex-ante predictions. To further facilitate the efficient implementation of the suggested resilience framework, specific PEI practices are discussed that support intra- and inter-agency coordination and engagement, while promoting the participation of network users in the decision-making process. The chapter also describes suggested key members of the PEI team.

In addition to the resilience assessment framework and the PDI and PEI suggested methodologies, agencies should consider a broader Database for Resilience comprising damage and non-damage data, relevant to the network performance assessment ex-ante and ex-post disaster events. Chapter 5 suggests a four-phase collection framework for building a resilience database:

(A) Asset classification and benchmarking.

(B) Monitoring normal operations.

(C) Data collection during or following the extreme event.

(D) Post-event performance and recovery metrics.

The data collection framework identifies the entire range of data useful for the assessment of post-disaster network condition and the evaluation of long-term resilience-building plans. The resulting resilience database could provide an overview of how the disaster has impacted both the highway infrastructure and the community.

Chapter 6 illustrates the application of the Highway Infrastructure Resilience Framework explained in chapter 2. For the demonstration case, the hazard considered is an earthquake; the asset portfolio comprises 13 highway transportation structures in New York State. To support resilience investment decisions, the Resilience Evaluation Tool (RET)[6] is used to evaluate the impact of two alternative investments (structural retrofit and installation and operation of accelerometers and displacement sensors) on the network seismic resilience.

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[6] The use of this tool is not a Federal requirement.

Chapter 2 Highway Infrastructure Resilience Framework

A framework was developed during this study to evaluate the resilience of highway infrastructure at a system level or at an asset-subgroup level, such as bridges or tunnels of a specific corridor. The suggested framework consists of a four-level organization: pillars, lenses, dimensions, and indicators. At the highest level, there are four (4) pillars: (A) functionality; (B) adaptability and operability; (C) database, post-event damage inspection (PDI) and post-event engineering investigation (PEI); and (D) multi-level governance. All four pillars could contribute to overall life quality in the communities served by these structures. The pillars are evaluated through various lenses that broadly address the Technical, Organizational, Socio-Economic (TOSE) resilience dimensions (Bruneau et al., 2003). Each lens is evaluated as a weighted sum of scores from one or all of the underlying dimensions. Finally, each dimension is evaluated by several indicators assigned to this dimension.

The goal of the resilience framework is to help transportation agencies and national and regional decision-makers to (A) benchmark the level of transportation infrastructure resilience, (B) track progress, and (C) identify areas that need strategic investment and ways that different stakeholders can contribute to transportation infrastructure resilience. The framework can be used to (A) evaluate pre-event risks and expected resilience levels, (B) rapidly prioritize emergency deployment post-event, (C) perform engineering evaluations with data collected post-event, and (D) evaluate the resilience benefits of potential remedial and improvement measures.

2.1 Highway Infrastructure Resilience

The 23 U.S.C. 101(a)(24) definition of resilience is applied to highway infrastructure exposed to multiple hazards and is quantified through aggregating: (A) the ability of its owners/managers to (i) anticipate and (ii) prepare for conditions and (B) the ability of its built components to (i) absorb extreme events, (ii) adapt to conditions, and (iii) achieve rapid recovery from disruptions throughout their life cycle.

This application of the resilience definition encapsulates aspects developed in the document "Recommended Options for Improving the Built Environment for Post-Earthquake Re-Occupancy and Functional Recovery Time" (FEMA, 2020) and other recent developments in the domain of lifelines resilience (Davis, 2019a; Davis, 2019b). This definition emphasizes the goal of functionality (or functional recovery), in addition to the traditional life safety goal. Functionality relates to targets that depend on the operational importance of the transportation assets/systems and their lifecycle. This definition also introduces the use of data-driven strategies and technologies (diagnostic, reconnaissance, visualization, emergency response, data collection, warning/messaging, etc.) to support decision-making in explicit resilience measurements and track the resilience improvement.

In addition, this definition supports the evaluation of the resilience concept using quantitative measures that can be applied in all stages of project planning, design, and construction, as well as operations/maintenance, and emergency response/recovery (Figure 2-1) (FHWA, 2018).

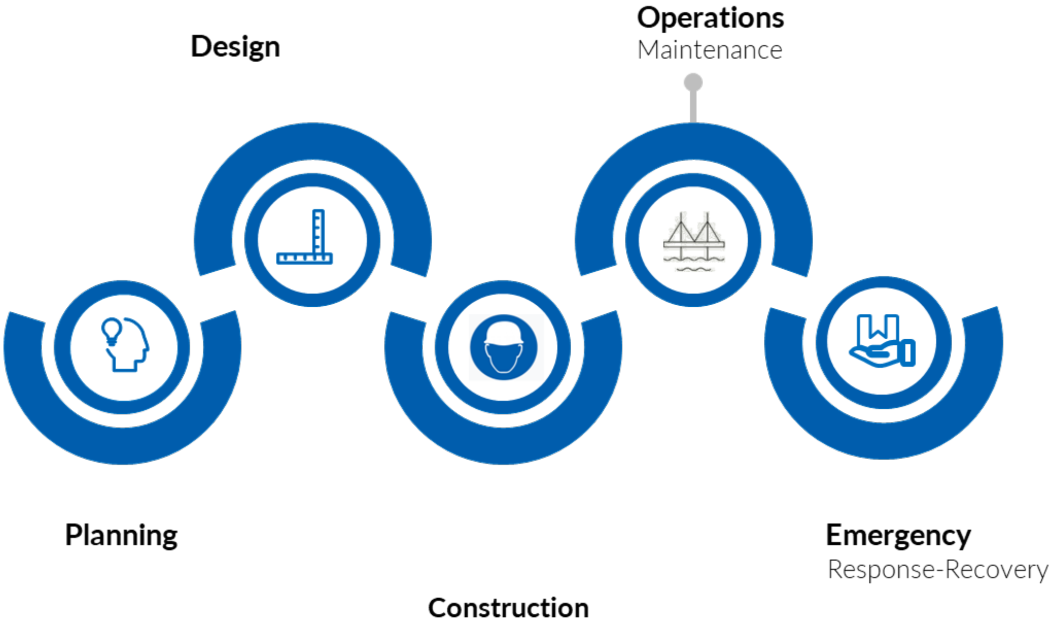

Figure 2-1: Highway Infrastructure Project Stages (image by the authors)

Generally, it is challenging to predict a project's "ability to anticipate, prepare for, or adapt to conditions or withstand, respond to, or recover rapidly from disruptions." (23 U.S.C. 101(a)(24)). This is because it is often difficult to measure the following for highway structures:

1. Design for extreme events.
2. Preparedness for extreme events.
    a. Readiness of decision-making.
    b. Resources and procedures in place. Resources include materials, equipment, and manpower.
3. Reaction to extreme events.
4. Ability to maintain the intended services with damage incurred during an event.
5. Reconnaissance ability to gather meaningful performance data to learn from events, and correct resilience shortcomings.
6. Ability to timely restore functionality.
7. Availability and usefulness of a resilience database.

Therefore, measuring resilience directly as the aggregate of reduction in services and intervention costs can become complex, involving analytical simulations of the highway infrastructure to determine the level of service before and after a disrupting event. Such simulations may not currently be a practical approach for evaluating the overall resilience of highway infrastructure due to the uncertainties and lack of actual case histories data. In addition, the occurrence of the extreme event could have cascading effects and trigger other hazards. These cascading effects are not accounted for by analytical simulations.

The developed framework in this study approaches the resilience evaluation by breaking it down into different categories at successive steps, presented in the methodology below, until reaching quantifiable indicators that capture the factors relevant to the highway infrastructure systems.

The nature of the developed framework is hierarchical and enables resilience measurement at different successive steps, while ensuring that the indicators are as independent and consistent as possible. The indicators are assigned numerical values. Calculations are then performed with these numerical values following a bottom-up approach that ultimately yields an overall resilience score. Part of the resilience assessment is hazard-specific and can be modified to address the individual needs of the hazards under consideration. The results for each individual hazard can be used, in comparison with the results of the other hazards, to support prioritization of retrofit/improvement actions, with the highest priority being the one with the lowest resilience score. The scoring can be assigned in the scale of the individual asset subgroups and can be adapted to evaluate the system as a whole as well.

Using the framework prior to extreme events, immediately after extreme events, and for post-events studies, can help to evaluate the levels of transportation infrastructure resilience, track progress, prioritize strategic investment, and support actions that can contribute to transportation infrastructure resilience.

2.2 Methodology

The developed framework evaluates resilience of highway infrastructure (for individual assets, also applicable to a system-wide scale) based on four (4) pillars: functionality; adaptability and operability; database, PDI, and PEI; and multi-level governance. The pillars are evaluated through various lenses that broadly address the TOSE resilience dimensions (Bruneau et al., 2003), which stand for T (technical), O (organizational), and SE (socio-economic). Finally, the lenses are evaluated by various indicators.

The methodology of the developed framework is outlined as follows:

1. Context of assessment: scale (asset vs. system), and exposure type (single-hazard vs. multi-hazard).
2. Risk assessment for the specified hazard(s).
3. Resilience assessment: assignment of weights and scores to the resilience indicators.
4. Resilience score calculation and identification of critical indicators/dimensions/lenses/pillars.
5. Development of resilience action plan/corrective measures and/or evaluation of different alternative resilience investments.

These steps are incorporated into the Resilience Evaluation Tool (RET) with a demonstration test case presented in chapter 6 of this report.

The identified indicators can be combined with assigned weights to revise the resilience score and emphasize the strengths and treat weaknesses within the highway asset and system, and eventually the region at large. The suggested assigned measurement scale for each indicator ranges from 4 to 1, with 4 being the most resilient and 1 the least resilient, as follows:

4: meets or exceeds all preferred performance.
3: acceptable performance, some improvements could be made.
2: less than desirable performance and specific improvements should be prioritized.
1: poor performance and improvements needed.

Regions and States can tailor their own specific measurement and weighting factors for indicators within each dimension under this proposed framework. Dimension weight can be modified for those under lenses that overarch multiple dimensions. The weight for each lens can also be customized to gauge the resilience of different pillars. These measurements and weighting factors should be defined by the owner that chooses to adapt the framework to ensure meaningful evaluations and comparisons. The suggested resilience evaluation can therefore be adapted in different contexts (hazard type, scale, time with respect to a certain hazard, location) by selecting the variables or indicators used for measurement and the weights used for scores computation.

2.2.1 Pillars

The four Pillars of the developed framework are shown on Figure 2-2**.**

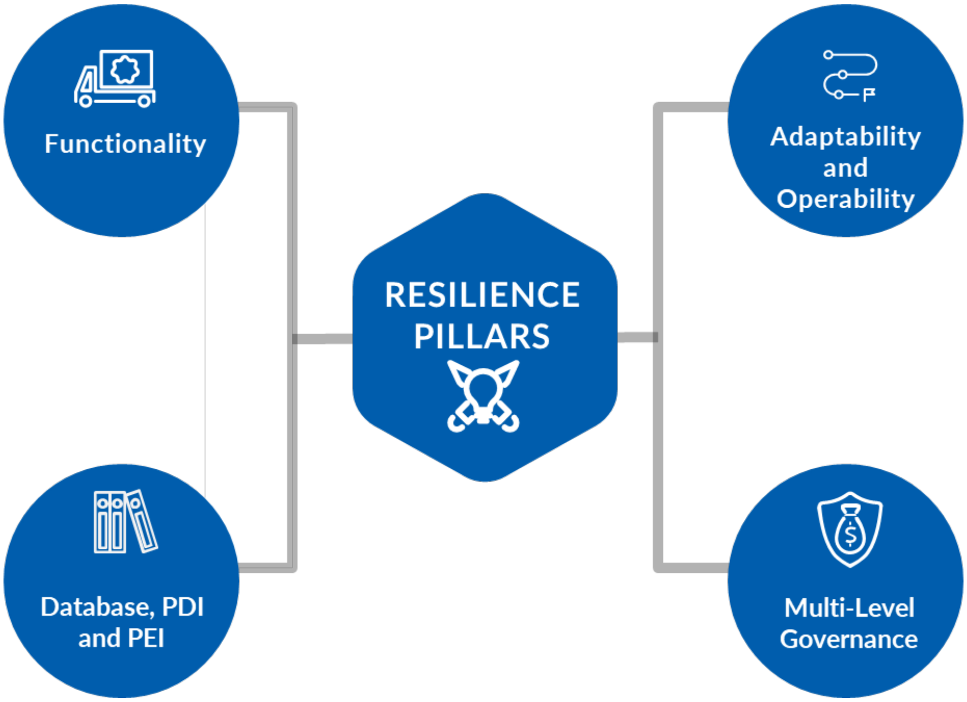

Figure 2-2: The four pillars of the developed framework for highway infrastructure resilience (image by the authors)

Each pillar represents the following fundamental qualifiers of resilience of highway infrastructure:

1. Functionality

   This pillar refers to the capability of the highway infrastructure to maintain, restore, and safely and adequately support the vital services and functions associated with the pre-event use considering defined levels of post-event service levels. Functionality describes the infrastructure performance, addressing both life safety and post-hazard functionality (or an acceptable damage level for a given hazard level), and measures the degree to which the infrastructure system is serving its intended purpose (SPUR, 2009).

2. Adaptability and Operability

   This pillar refers to the ability of a highway infrastructure to remain usable following the extreme event as it undergoes changes imparted by the hazard, while still providing operability. This pillar reflects that resilience is not simply about being able to survive or return to the starting point after a shock, but rather it represents a proactive and adaptive capacity in the face of the changing environment. The key differentiator between the Functionality and the Adaptability pillars is that the Functionality pillar refers to how the system reacts to an event and returns to a specific state, while Adaptability pillar refers to how the system adapts to operate under changed conditions.

3. Database, PDI, and PEI

   This pillar refers to sourcing, using, and sharing data and best practices for effective pre-event planning and post-event response, recovery, and rebuilding. It considers asset management, emergency and reconnaissance protocols, framework and protocols for gathering engineering quality performance data and establishment of a database, training for preparedness and reconnaissance, and recommendations for post-event response. This pillar is key to documenting and using lessons that have been learned from past and ongoing events, and to developing the ability to anticipate and prepare for future events. In fact, actual data can be used to improve codes and standards, as well as emergency planning, and to build resilience in infrastructure projects.

4. Multi-Level Governance

   This pillar refers to the multiple layers of oversight, guidance, and support involved with the highway infrastructure owner/manager. This layering is important in buildings resilience in the system. This pillar includes organized governmental services, as well as institutionalized planning and response networks, in order to answer the question of how highway infrastructure needs to be managed, thereby boosting their resilience against extreme events.

The four pillars have been identified based on a literature review. This review also found that qualitative approaches for undertaking resilience assessments tend to be more practical, flexible, and adaptable to different scales (asset, system/network, region) and hazards than purely quantitative approaches. Highway infrastructure resilience metrics can have more value when transformed from continuous to categorical data and ordinal rankings. For these reasons, the developed framework can be overall characterized as qualitative, even though it includes quantitative indicators. The resulting single composite score resilience and the underlying multiple individual scores corresponding to pillars, lenses, and TOSE dimensions are intended to support decisions during the stages of planning, engineering design and construction, operation, and emergency response and recovery of highway infrastructure systems.

2.2.2 Lenses

The four pillars are evaluated by the lenses shown on Figure 2-3, which are evaluated by objectively quantified indicators. A highway infrastructure should ideally satisfy the physical, social, economic, and environmental wellness of its users. These may be summarized as elements of Life Quality. Indicators of Life Quality could encompass community readiness, access to vital services, and business continuity.

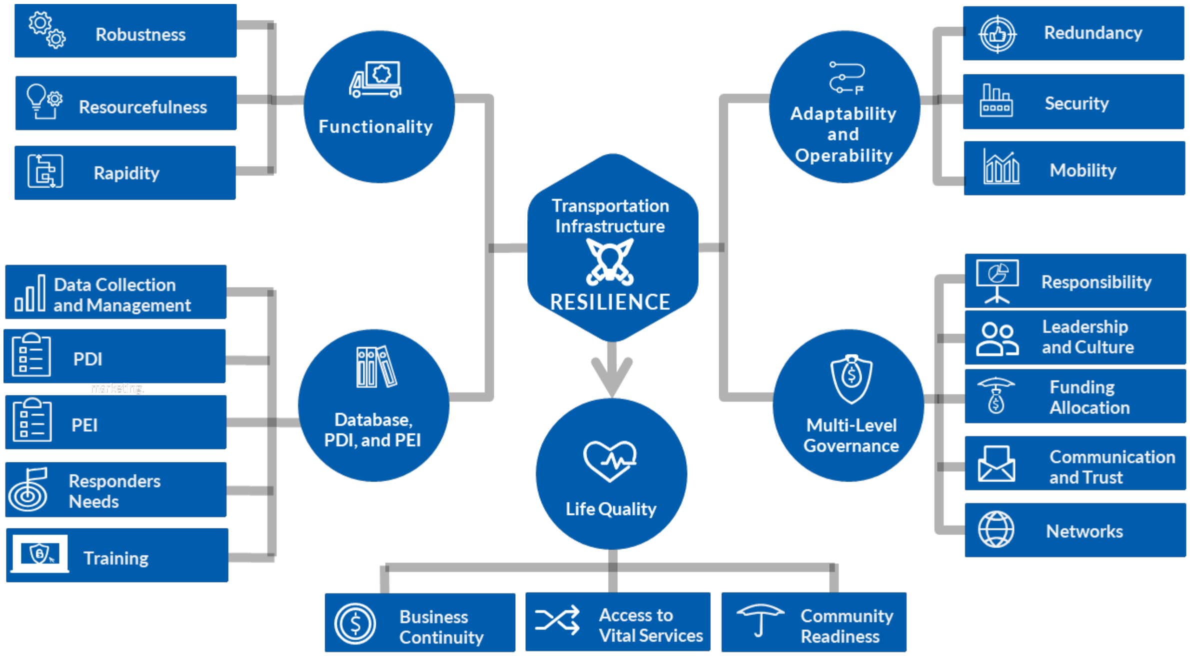

Figure 2-3: Resilience Pillars and Lenses (image by the authors)

2.2.3 Indicators and Dimensions

The indicators are the finest level of the resilience assessment in the developed framework and evaluate the pillars through their corresponding lenses. They are selected based on consideration of the assessment scale, availability of information, level of effort to collect needed information, and their relevance and connection to decision-making. Transportation infrastructure resilience is linked to "systems thinking," which conceptualizes the system itself as both part of larger systems and comprised of smaller systems. The larger systems include the communities and their economies, societies, environments, and governments. The smaller systems consist of the individual transportation assets such as highways, tunnels, and bridges.

The indicators of each lens are classified as contributing to one of the TOSE dimensions of resilience. This enables separate measurement of each dimension to determine where to concentrate the limited resources to improve resilience. Figure 2-4 through Figure 2-7 show the indicators under each pillar and respective lenses, grouped based on TOSE dimensions. All the lenses under the "Database, PDI, and PEI Practices" pillar and the "Multi-Level Governance" pillar fall under the Organizational dimension, which is not repeated in Figure 2-6 and Figure 2-7. The TOSE dimensions are described as follows:

1. Technical: relates to performance levels of the built environment (components, interconnections, and entire systems) subjected to extreme events.
2. Organizational: reflects the ability of an organization that manages facilities and responds to extreme events to enhance some common characteristics of resilience, such as robustness, redundancy, resourcefulness, rapidity.
3. Social: represents the ability to reduce the impacts that communities and governmental authorities suffer from after extreme events as a result of technical losses.
4. Economical: relates to the reduction of direct and indirect economic losses due to extreme events.

The list of indicators presented in Figure 2-4 through Figure 2-7 applies to a generic multiple-hazard assessment. This list can be a starting point for developing resilience indicators suited for a hazard-specific assessment on asset and system scales. Each identified indicator is quantified by a number between 1 (lowest resilience) and 4 (highest resilience).

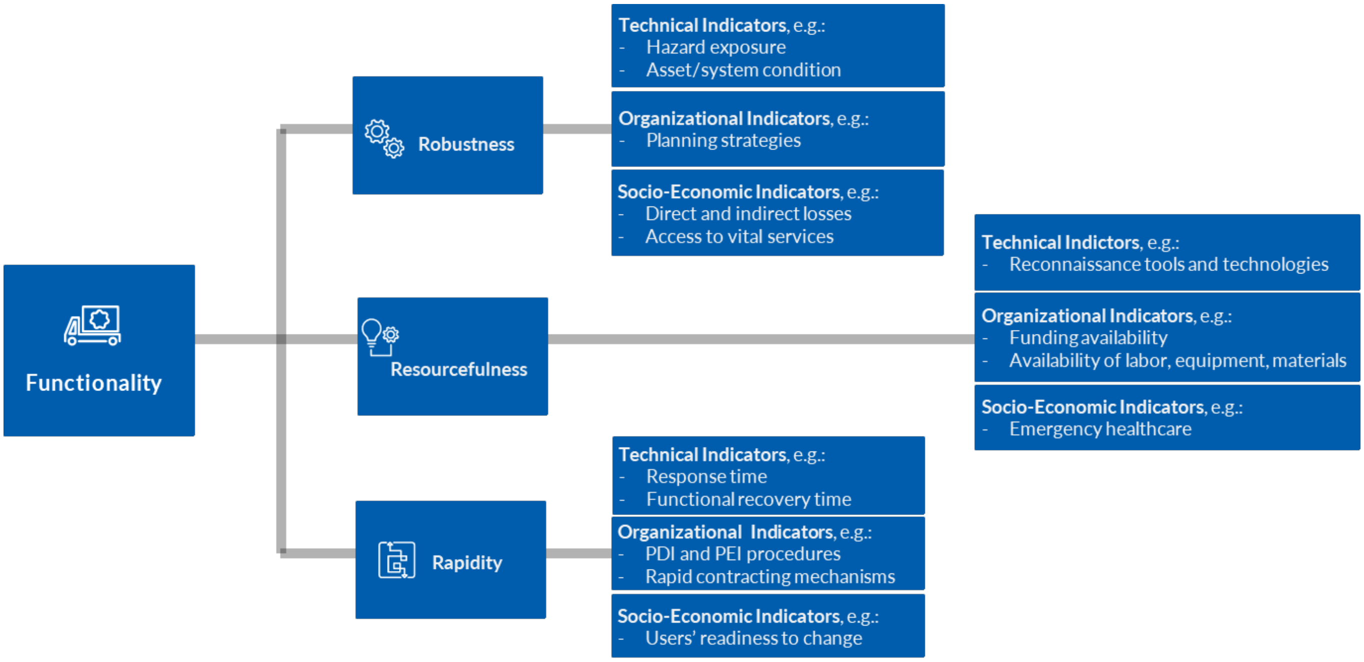

Figure 2-4: Functionality Indicators (image by the authors)

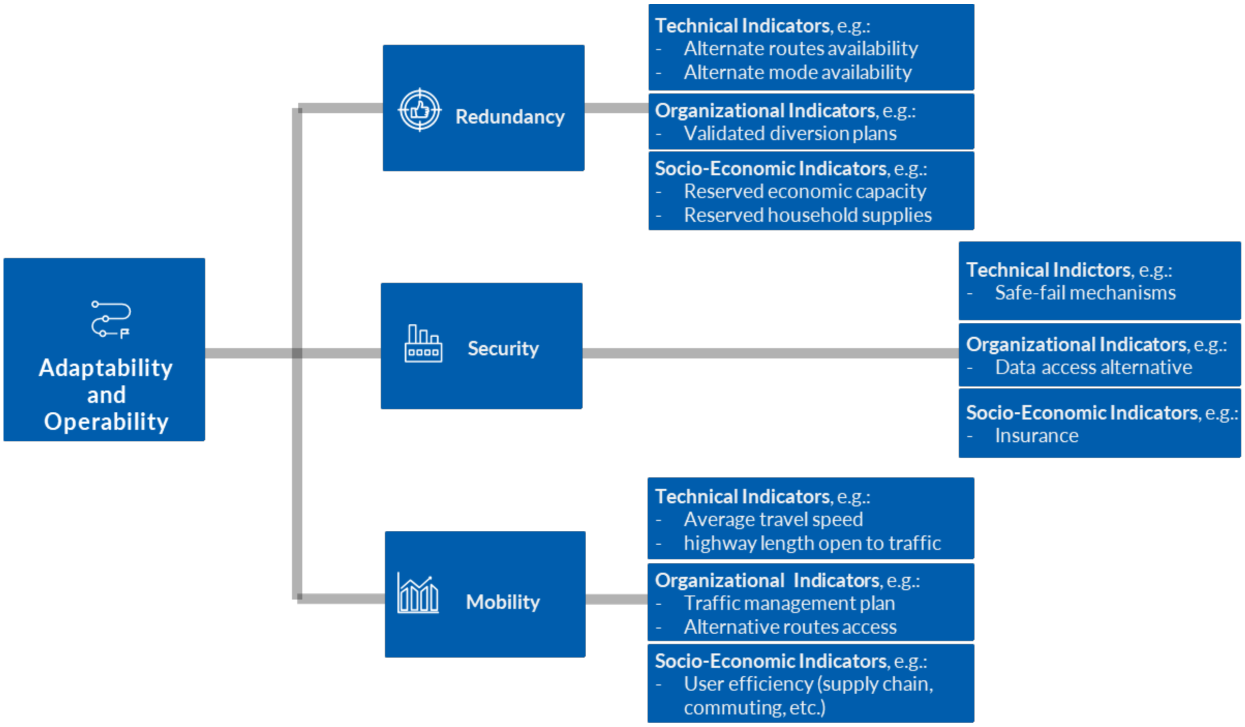

Figure 2-5: Adaptability and Operability Indicators (image by the authors)

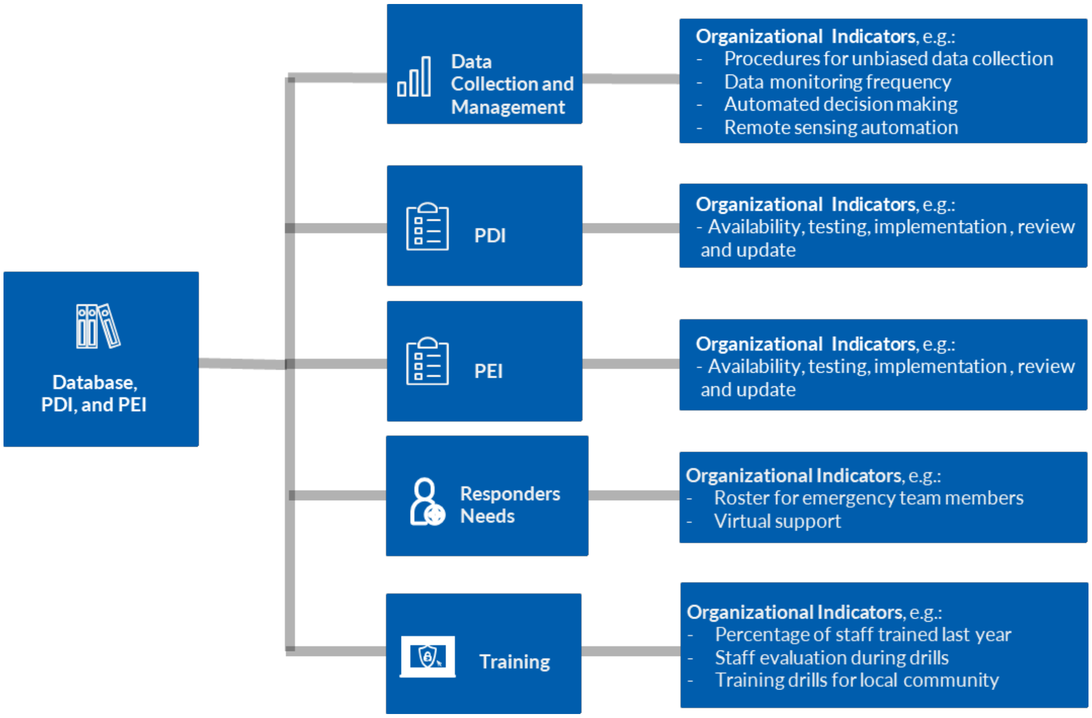

Figure 2-6: Database and PDI-PEI Indicators (image by the authors)

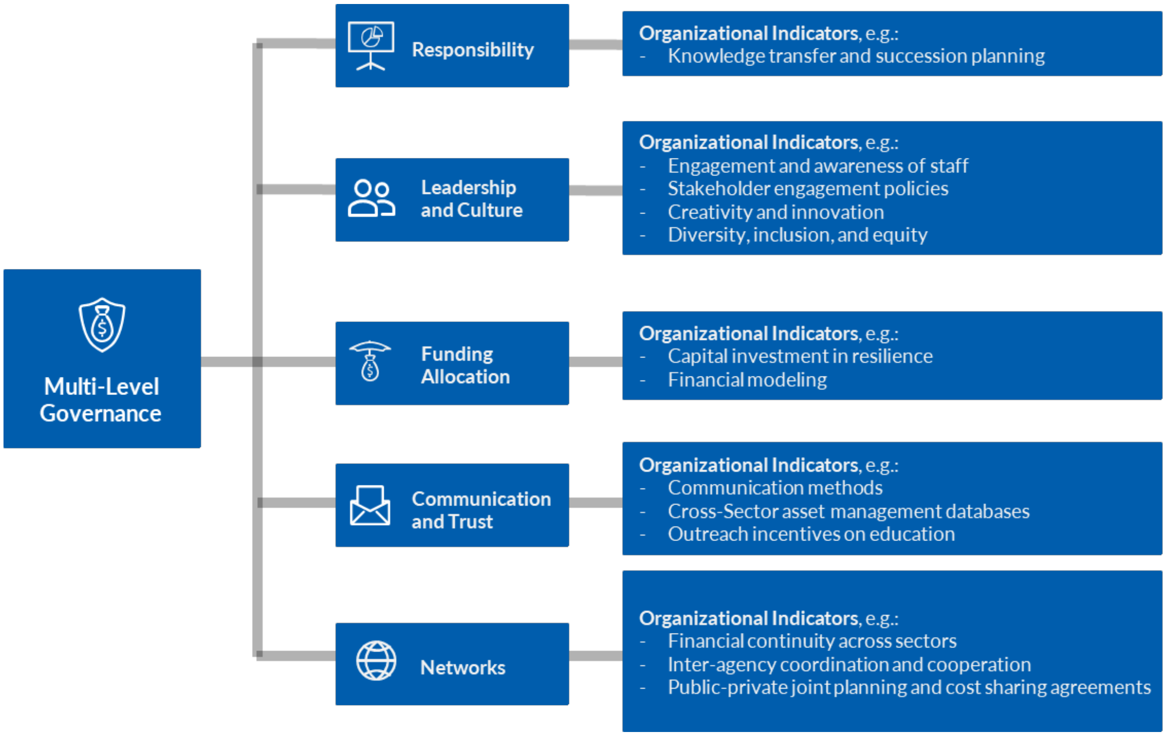

Figure 2-7: Multi-Level Governance Indicators (image by the authors)

2.3 Treating Uncertainties

Few cross-cutting themes are found to influence the presented resilience assessment framework.

2.3.1 Assignment of Weights

Weights can be applied at the pillar, lens, dimension, or indicator level. The weightings are numbers with up to two decimal places ranging between 0.00 and 1.00. and must add to 1.00 across each level. The weights allow the user to prioritize based on importance or degree of certainty of the data for one pillar, lens, dimension, or indicator over another.

For example, one agency may determine that the Functionality pillar of resilience is more important than the Adaptability and Operability pillar, Database, PDI, and PEI pillar, and Multi-Governance pillar and consequently allocate weights of 0.40:0.20:0.20:0.20, respectively. Therefore, the weights are based on user judgement or successful applications in past case studies. However, to mitigate bias and a subjective resilience assessment, weights should be developed in a group setting and with stakeholders having appropriate and broad knowledge, independently of score assignment. In addition, the individual weights can be reviewed and interrogated to determine the rationale behind a specific indicator, dimension, lens, or pillar weight.

In the absence of a clear agreement that a certain indicator, dimension, lens, or pillar is of more or less relevance than the others, weights may be set evenly across one level. In some cases, the use of a certain indicator may not be appropriate due to lack of data or poor data quality. In this case, the indicator weight may be reduced or may take the value of 0.00 to completely remove the indicator from the assessment. If the results of different resilience assessments are to be compared across different States or regions, then a consistent rationale should be followed when assigning weights.

2.3.2 Scale of Resilience Assessment: Asset vs. System

The resilience assessment can be tailored for an individual asset (or a component) of the highway infrastructure (e.g., bridge) or the system as a whole (e.g., highway with several bridges). The technical dimensions of the pillars of Functionality and Adaptability/Operability pillars can be adjusted for an individual asset or a system assessment. In the individual asset case, a single value for each technical indicator would apply. In contrast, in the system-wide case, each indicator would reflect the percentage of assets which satisfy target performance levels for these pillars.

2.3.3 Interactions between the various selected pillars and lenses of resilience

Although the pillars and lenses are selected to cover the resilience elements identified by the literature review, it is important to note the complex interactions between them. These interactions make it difficult to capture a single comprehensive score of resilience. To rectify this issue, consider measuring resilience at any desired level (dimension, lens, pillar). Comparing the different scores pertaining to the same level could provide more insight than looking at the overall resilience score alone.

Chapter 3 Post-event Damage Inspection Needs and Suggestions

The chapter presents an enhanced methodology for Post-Event Damage Inspections (PDI), based on identified needs and gaps within the state-of-practice PDI procedures, protocols, and emergency response plans. Available PDI procedures by State DOTs, Federal organizations, and research institutes were reviewed prior to developing the suggested methodology. The methodology aims at improving highway infrastructure resilience against extreme events, as measured using the framework described in chapter 2. If a resilience indicator depends on more than one PDI action, a distinct score is assigned to the resilience indicator for each PDI action item, and the final indicator score may be calculated as the average value of individual scores. The scoring approach is developed for the convenience of any interested organizations as an option when such quantitative measure is beneficial. It does not imply any requirements or establishment of new standards.

3.1 Pre-Event Planning

Proactive disaster planning can lead to expedited recovery and significant cost reduction in the long run, (Olsen et al. 2016a)[7]. However, considerations prior to a disaster event for all hazards and structures of interest may differ between State DOTs, and therefore may not be consistent or sufficiently corroborated. This section suggests ways to address the identified needs in current pre-event planning procedures.

3.1.1 Digital Infrastructure and Data Management

A small number of web-based, Geographic Information System (GIS) compatible, real-time-data-fed applications were identified in the synthesis of practices. U.S. Geological Survey (USGS) ShakeCast, the USGS ShakeMap Broadcast; California Department of Transportation (Caltrans) Climate Change Vulnerability Assessment Map are among examples. Some of the available tools comprise some form of offline calculation spreadsheets, while others are offline software with minor interconnectivity to data-collection systems or applications. More comprehensive and interconnected extreme event GIS resources can increase the efficiency of post-event response endeavors and reduce response time. Further, more consistent data formatting across the different levels of damage assessment can facilitate better integration and dissemination of accurate data. Benefits of consistency may come from practices in data collection, operation of pre-disaster evaluation tools, notification of the emergency response team, and notification of the public. Several key attributes of database architecture, digital infrastructure, and data management that enhance the efficiency of emergency response are listed below.

3.1.1.1 Digital Inventories and GIS Systems

Olsen et al. (2016a) indicated that lead agencies would benefit from developing digital inventory databases for all assets of interest, connecting structures to their geospatial location, traffic levels, condition, and other pertinent information. Robust nationwide inventories containing such information have already been compiled by FHWA for bridge (National Bridge Inventory [NBI][8]) and tunnel structures (National Tunnel Inventory [NTI][9]) yet are still to be developed for other highway assets, such as geo-structures. Moreover, data from past disruptive events are typically not incorporated in such inventories; hence there is not an abundance of data of how these structures perform during and after a disruptive event. Such observations could be of value to the development and calibration of catastrophe models, as well as the production of more reliable results from pre-disaster planning tools. Informed digital inventories can help with structure prioritization, coordination of damage assessments in the aftermath of an event, as well as the determination of asset vulnerability. State-level structural databases should be cross-checked for data inconsistencies with national level databases, while standard timelines (e.g., every year) should be established for their review/update. Through the development of organized and

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[7] Note that the suggestions, methods, procedures, and other information taken from the NCHRP Research Report are included for informational purposes only and are not Federal requirements.

[8] https://www.fhwa.dot.gov/bridge/nbi.cfm

[9] https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm

systematic databases, information during PDI operations can be retrieved, compared, and analyzed in a GIS environment. It could prove helpful for lead agencies to invest in the development of a GIS infrastructure (software and hardware) to assist these efforts.

3.1.1.2 Compatible Systems Architecture for Data Integration

Lead agencies may benefit from investments in interoperable asset and emergency management platforms for a holistic highway asset management. Existing asset management platforms may be customized to allow a compatible architecture between asset and emergency management systems, which would grant data interconnectivity and integration. With this interconnectivity, disaster management systems should be able to instantly draw regular maintenance data, and feed critical decision-making at the time of the disaster. Collected post-disaster inspection data can also feed into asset management platforms, thereby allowing informed vulnerability assessments, that produce asset and network resilience ratings in the aftermath of the event.

3.1.1.3 Traffic Information

Frequently updated highway route topologies and traffic information could be incorporated into GIS databases for use during PDI operations. Network capacity, traffic levels (e.g., in terms of Annual Average Daily Traffic) and the composition of traffic (light vs. heavy vehicles) could assist in determining critical structures within the transportation network. This information may be used by traffic engineers in a disaster event, to make informed decisions on appropriate detour routes and reduce traffic congestion problems in the event of closure of a damaged structure, as well as to help with the prioritization of asset inspections in the aftermath of a disaster.

3.1.2 Pre-Event Evaluation Tools and Analyses

Lead agencies may benefit from using predictive hazard forecasts and hazard mapping tools, along with proper assessment tools (nationwide or at a State level) for the ex-ante evaluation of vulnerability and damage of the highway assets. It is important to link pre-event emergency planning with scenario-based analyses to decide upon expected damage from various hazard sources.

Table 3-1 to Table 3-3 provide an overview of available pre-evaluation tools/practices for three hazards (earthquake, flood, and fire) in a number of State DOTs that have already established Emergency Response Plans for those hazards. The gap analysis revealed limited availability of pre-event vulnerability assessment tools in several State DOTs, and even for those with such tools in place, not every vulnerable-to-hazard highway asset was analysed.

In the case of probabilistic vulnerability assessment tools such as ShakeCast and Federal Emergency Management Agency (FEMA) Hazards U.S. Multi-hazard (HAZUS-MH), State DOTs could develop their own state-wide fragility curves for the hazards of interest (Olsen et al., 2016a). Utilization of generic fragility functions build-in within various software (as in the case of Hazus-MH) could lead to less accurate vulnerability results during scenario-based analyses. Furthermore, State DOTs may use a component-level fragility approach for a more detailed probabilistic damage assessment of assets.

State-of-the-art Pre-Disaster Evaluation (PDE) tools should conform to minimum technological practices in terms of GIS functionality and interconnectivity/interoperability with asset management platforms and external hazard data sources. Routine inspection data could be incorporated into scenario-based analyses to allow for informed risk assessments based on the current condition of assets. Scenario-based analyses can be reviewed and updated regularly to include the most recent structural condition or hazard data.

Some existing software, such as Hazus-MH, relies on a separate GIS package. Using integrated GIS within the software would allow for technological updates to be directly applied to the software package as it evolves.

Resolution of imported spatial data should be checked and deemed appropriate for vulnerability assessments at the component level to ensure accurate predictions of asset risk. Spatial data include elevation or bathymetry data, hazard data such as the earthquake intensity, or down-scaled climate data from general circulation models such as precipitation projections. In the event of reduced resolution of data stemming from Nation-wide platforms, lead agencies may employ local (State-wide) data of higher resolution.

Finally, it may be beneficial for the employed PDE toolkits to include a loss estimation module to translate asset damage to direct and indirect losses information for preliminary cost estimates.

Table 3-1: Availability of pre-event evaluation tools for earthquake hazard in State DOTs that have relevant PDI procedures in place.

State DOT	Availability	Tool
New York State DOT	-	(none)
Utah DOT	✓	ShakeCast[10]
Alaska DOT	-	(none)
Caltrans	✓	ShakeCast[1], REDARS 2™[11]
Oklahoma DOT	✓	ShakeCast[6]
Oregon DOT	✓	ShakeCast[6]
Indiana DOT	✓	HAZUS-MH[12]
Iowa DOT	-	(none)
Kentucky DOT	-	(none)
Mississippi DOT	✓	ShakeCast[6]
Washington DOT	✓	ShakeCast[6]
Ohio DOT	-	(none)

Table 3-2: Availability of pre-event evaluation tools for climate change and flooding in State DOTs that have relevant PDI procedures in place.

State DOT	Availability	Tool
Ohio DOT	✓	FHWA Vulnerability Assessment Scoring ToolVAST[13]
Maryland State Highway Administration	✓	FHWA Vulnerability Assessment Scoring Tool + CCVV[14]
Caltrans	✓	Caltrans Climate Change Vulnerability Assessment Map[15]

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[10] http://usgs.github.io/shakecast/2017_shakecast_dot_tpf.html

[11] Werner, S. D., Cho, S., Taylor, C. E., Lavoie, J.P., Huyck, C. K., Chung, H., and Eguchi, R. T. (2006). Redars 2 methodology and software for seismic risk analysis of highway systems. Report MCEER-06-SP08, Buffalo NY: Multidisciplinary Center for Earthquake Engineering Research, March.

[12] Indiana Department of Homeland Security and the Polis Center Indiana University-Purdue University Indianapolis (2019) State of Indiana Standard Multi-hazard Mitigation Program.

[13] RSG (2016). Ohio DOT Infrastructure Resiliency Plan. Final Report. Prepared for: Ohio Department of Transportation

[14] Bhat, C., Wagner, H., Cherry, C., and Habic, E. (2019). Integrating Extreme Weather and Climate Risk into MDOT SHA Asset Management and Planning: A Final Report from the FHWA Asset Management, Extreme Weather, and Proxy Indicators Pilot Program.

[15] https://www.arcgis.com/apps/webappviewer/index.html?id=517eecf1b5a542e5b0e25f337f87f5bb

Table 3-3: Availability of pre-event evaluation tools for wildfires in State DOTs that have relevant PDI procedures in place.

State DOT	Availability	Tool
Caltrans	✓	Caltrans Climate Change Vulnerability Assessment Map
Utah DOT	✓	Utah WRAP[16]

3.1.3 Inspection Prioritization and Response Levels

3.1.3.1 Inspection Prioritization

It is beneficial to develop a prioritized list of routes and structures that should be inspected first, to reduce network disruption and ensure safe public traveling. The owners/operators of the highway system or corridor could invest in a GIS-based prioritization program to assist in the systematic prioritization of inspected routes and structures during disaster response operations. The tool could display attributes such as the following:

- A route prioritization module fed by hazard data (earthquake, wind, surge, riverine flooding, etc.), population data, social demographics and traffic data (including network capacity and traffic levels). The module should include a priority route scoring system based on identified lifelines per hazard, to result in specific areas of interest, lists of priority inspection routes, and efficient detour alternatives that minimize traffic disruptions. Agencies may use and/or customize FEMA's Prioritization Operations Support Tool[17] or a similar toolkit for this purpose.

- A structures prioritization module fed by hazard and structural vulnerability data, which should be able to produce prioritization lists for structures inspections within the area of interest. PDE toolkits used in scenario planning can prove very useful in identifying vulnerable sections of the highway, as well as vulnerable structures for preliminary route prioritization (Olsen et al., 2016a).

Each owner agency should define its own criteria with which priority levels are set, and subsequently incorporate them into the software. For example, a State DOT may heavily rely on structural vulnerability, while other State agencies may rely more on social criteria, population data, or the minimization of disruption in traffic operations for the development of prioritization lists. Based on the prioritization analyses outlined above, lead agencies may develop and regularly update emergency traffic management plans, tailored to specific emergency events.

3.1.3.2 Response Levels

Response levels are associated with the level of resources activated during an agency's post-disaster response. They typically assist lead agencies in prioritizing resource allocation, determining which assessment stages are necessary, and identifying the need for outside resources. The use of response levels identified in the National Cooperative Highway Research Program (NCHRP) Research Report 833, Volume 2, is suggested for the following emergency events: earthquake, tsunami, tornado and high wind, hurricanes, storm surge, flooding, and fire (Olsen et al., 2016a). These response levels may act as the base reference for lead agencies, but agencies may also benefit from establishing or re-establishing the magnitudes associated with each response level per emergency event, based on experience in the specific hazard, the vulnerability of structures, and the intensity levels associated with historical damage from this hazard. State DOTs with a "Rapid Response" module embedded in their PDE framework (see section 3.2.3) could use near real-time data following an event, to obtain a better overview of the extent of damage and assist decision-making regarding the appropriate allocation of resources.

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[16] https://wildfirerisk.utah.gov/

[17] https://www.arcgis.com/home/item.html?id=e9bfa3d9a96e42858062832af4de280b

Identifying post-event needs based on the response level and having pre-event agreements in place regarding property access, material supply, and services contracting (e.g., consulting, surveying, construction, etc.) could help expedite a State DOT's response and PDI efforts.

Table 3-4: Connection of "3.1. Pre-event Planning" with the Resilience Evaluation Tool. The adopted "Pre-event Planning" procedures increase the score of the following measures up to 4.

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Functionality	Resourcefulness	Technical	*"Data Visualization, GIS"*	*3.1.1. Digital Infrastructure and Data Management [Digital Inventories and GIS systems]*
Functionality	Resourcefulness	Organizational	*"Crisis Decision-Making"*	*3.1.2. Pre-Event Evaluation Tools and Analyses;* *3.1.3. Inspection Prioritization and Response Levels*
Functionality	Resourcefulness	Organizational	*"Pre-event Recovery Planning"*	*3.1.1. Digital Infrastructure and Data Management;* *3.1.2. Pre-Event Evaluation Tools and Analyses;* *3.1.3. Inspection Prioritization and Response Levels*
Functionality	Robustness	Socio-economic	*"Direct and Indirect losses"*	*3.1.2. Pre-Event Evaluation Tools and Analyses*
Functionality	Robustness	Socio-economic	*"Access to vital services"*	*3.1.2. Pre-Event Evaluation Tools and Analyses;* *3.1.3. Inspection Prioritization and Response Levels [Inspection Prioritization]*
Functionality	Robustness	Organizational	*"Planning Strategies"*	*3.1.1. Digital Infrastructure and Data Management;* *3.1.2. Pre-Event Evaluation Tools and Analyses;* *3.1.3. Inspection Prioritization and Response Levels*
Functionality	Rapidity	Technical	*"Prioritization Criteria"*	*3.1.3. Inspection Prioritization and Response Levels*
Functionality	Rapidity	Organizational	*"Emergency Vehicles Routes Planning"*	*3.1.1. Digital Infrastructure and Data Management [Traffic Data];* *3.1.3. Inspection Prioritization and Response Levels [Inspection Prioritization]*
Functionality	Rapidity	Organizational	*"Rapid Contracting Mechanisms"*	*3.1.3. Inspection Prioritization and Response Levels [Response Levels]*
Database, PDI and PEI practices	Data Collection and Management	Organizational	*"Geospatial Visualization"*	*3.1.1. Digital Infrastructure and Data Management;* *3.1.2. Pre-Event Evaluation Tools and Analyses*
Database, PDI and PEI practices	Data Collection and Management	Organizational	*"Database Updating Procedures"*	*3.1.2. Pre-Event Evaluation Tools and Analyses*

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Database, PDI and PEI practices	Data Collection and Management	Organizational	*“Automated Decision Making”*	*3.1.1. Digital Infrastructure and Data Management* *3.1.2. Pre-Event Evaluation Tools and Analyses;* *3.1.3. Inspection Prioritization and Response Levels*
Database, PDI and PEI practices	Data Collection and Management	Organizational	*“Information Backup”*	*3.1.1. Digital Infrastructure and Data Management*
Adaptability and Operability	Security	Technical	*“Risk Assessment and Scenario Planning”*	*3.1.2. Pre-Event Evaluation Tools and Analyses*
Adaptability and Operability	Redundancy	Technical	*“Alternate Routes Availability”*	*3.1.1. Digital Infrastructure and Data Management [Traffic Data];* *3.1.3. Inspection Prioritization and Response Levels [Inspection Prioritization]*
Adaptability and Operability	Redundancy	Technical	*“Alternate Modes Availability”*	*3.1.1. Digital Infrastructure and Data Management [Traffic Data];* *3.1.3. Inspection Prioritization and Response Levels [Inspection Prioritization]*
Adaptability and Operability	Redundancy	Organizational	*“Validated diversion plans”*	*3.1.1. Digital Infrastructure and Data Management [Traffic Data];* *3.1.3. Inspection Prioritization and Response Levels [Inspection Prioritization]*
Adaptability and Operability	Mobility	Organizational	*“Traffic Management Plan”*	*3.1.1. Digital Infrastructure and Data Management [Traffic Data];* *3.1.3. Inspection Prioritization and Response Levels [Inspection Prioritization]*

3.2 PDI Procedures

The PDI stages presented below build upon the procedures described in Olsen et al. (2016a) for assessing highway structures following the occurrence of natural disasters, yet are updated to reflect the practices of the suggested PDI methodology. The procedure described in Olsen et al. (2016a) is largely based on approaches used by several State DOTs (including the State DOTs of New York, Washington, Utah, and California) reporting four main stages of post-event damage assessment, as follows:

- *Fast Reconnaissance* (FR), typically occurring within 4-6 hours from the disaster event.
- *Preliminary Damage Assessment* (PDA), typically occurring within 24-48 hours from the disaster event.
- *Detailed Damage Assessment* (DDA), typically occurring within 8 hours after PDA.
- *Extended Investigation*, occurring after DDA.

Note that these stages are prescribed by Olsen et al. (2016a) and are not related to FHWA’s ER program. Olsen et al. (2016a) does not refer to any statutory or regulatory requirements.

This section provides suggestions for the main PDI agenda, starting with event notification and concluding with the DDA stage. Besides the FR, PDA, and DDA stages, several assisting and parallel processes are also discussed. These processes are relevant to the rapid damage assessment of highway assets in the aftermath of an event, the PDI communication and coordination procedures, road closures, and detour activities. The Extended Investigation stage is not included from this section, receiving special mention within chapter 4, which is dedicated to post-event engineering investigation procedures.

These procedures are separate from FHWA's Emergency Relief (ER) Program. For more information on the ER program, *see* 23 U.S.C. 125.

3.2.1 Event Notification

Lead agencies typically receive notification of an emergency event from a source usually operating at a Federal level, such as the National Oceanic and Atmospheric Administration (NOAA) or USGS, and less frequently from regional weather stations or acceleration networks. Upon notification receipt, a State DOT commonly activates the associated Emergency Response Plan (ERP). Earthquake-affected lead agencies, for example, typically maintain a subscription to USGS's Earthquake Notification Services (ENS), a free service that sends automated notification emails when earthquakes occur in a defined area of interest.

3.2.2 Fast Reconnaissance

FR occurs to determine the geographic extent of damage, decide upon the appropriate response level, and inform the prioritization of on-the-ground assessments. Members of the PDI Emergency Response Team (ERT) involved in the FR process may at least include the Emergency Management Coordinator (EMC), the FR Coordinator (FRC), the Assistant EMC, and Office Support Staff. For further details on the ERT composition and contributions see section 3.3. The methodology recommends a narrow list of FR data gathering methods (Table 3-5).

Table 3-5: Typical FR data gathering methods.

FR Data Gathering Method	Examples of Available Resources	Availability
Helicopter or small aircraft-based aerial survey	Typical practice for most lead agencies	Commonly used
Rapid remote sensing providing visually interpretable images (Aerial Imaging/Lidar Reconnaissance/Satellites)	- USGS Hazard Data Distribution System - The International Charter (www.disasterscharter.org)	Available for use
Low-cost Unmanned Aircraft System-based imaging	North Carolina DOT and others (Murphy, 2019)	Available for use
Advanced GIS integration and interoperability technologies	- Web-based Disaster Response GIS services from commercial service providers.	Emerging
Crowdsourcing (public)	- USGS: Did You Feel It?	Available for use

Out of the four methods presented in Table 3-5, the first three are currently available for use during an extreme event, with the first being the standard practice among lead agencies (Olsen et al., 2016a). It comes, however, at a large cost and is associated with high accident risks. On the other hand, rapid remote sensing FR technologies can be very useful for rapidly acquiring information from regions impacted by natural hazards, without traveling to the impacted site. Tools such as the USGS Hazard Data Distribution System and the International Charter can be used to assess broad-area damage in a particular region from high resolution images immediately after an event.

Satellite imagery is typically used for an initial high-level screening of the damaged region. Compared to both manned and unmanned aerial collection methods, satellite imagery often has lower resolution.

Generally, Unmanned Aerial System (UAS)-based reconnaissance procedures and GIS-based preliminary damage mapping offer benefit for FR. The first provides high resolution and naturally higher reliability of data associated with aerial surveys, combined with the lower costs and risks compared to helicopter or small aircraft-based aerial surveys. The procedure needs trained and licensed UAS operators, along with coordination with the Federal Aviation Administration to ensure compliance with respective regulations. The second provides crucial information rapidly (assembly of critical structures in a digital mapping product and generation of optimal inspection routes), thereby eliminating time lags in the decision-making process between the FR and the PDA.

The study also sees potential in FR data gathering methods via crowd-sourced data. Crowd sourcing assists in rapid post-disaster crisis mapping via tools that rely on raw/unstructured data from the social media, or via crowdsourcing-based applications that engage the public as reporters or micro-taskers.

3.2.3 Rapid Damage/Loss Assessment

PDE toolkits available for scenario-based analysis could be extended to serve as rapid response tools following the FR stage. For a rapid response functionality, the toolkit should have a data structure compatible with available real-time hazard platforms (e.g., USGS ShakeMap or NOAA's Hurricanes and Extreme Storms web viewer). Lead agencies may utilize real-time data for post-disaster rapid condition screenings to update inspections prioritization lists. As a result, deployment teams can be directed to highway components/links that are most severely damaged or are likely to have injured people.

Lead agencies may use already available rapid response tools for post-event vulnerability screenings, such as ShakeMap and ShakeCast in the case of earthquake hazard. However, the existence of a loss estimate module is not currently available in ShakeCast. Such a module is expected to greatly enhance the potential of a rapid response tool.

3.2.4 Preliminary Damage Assessment

The PDA is meant to facilitate the quick inspection and assessment of highway structures in the damaged areas determined to be at risk from the FR stage, following priority routes and pre-determined structures prioritization lists. Members of the ERT involved in the PDA process could include the EMC, the Managing Engineer, the Assistant EMC, PDA Responders (PDARs), the Emergency Data Coordinator, and Office Support Staff. For further details on the ERT composition and contributions see section 3.3.

3.2.4.1 Equipment

PDARs in teams of two typically are deployed to evaluate damage on the most critical highway assets, typically by means of visual inspections. The use of smart devices that embed digital maps, digital cameras, global positioning system (GPS), reporting, and communication is suggested in this phase. Marking supplies and more conventional tools such as cloth or tape measures, level, compass, and laser distance measures are also used. Olsen et al. (2016b) has a more extensive checklist of suggested field inspection supplies for PDA.

3.2.4.2 Damage Assessment

The PDA procedure could follow the suggest methodology and steps described in chapter 3.4. of the NCHRP Research Report 833, Volume 3, Coding and Marking Guidelines for Highway Structures in Emergency Situations (Olsen et al., 2016b), or any similar methodology already in place by lead agencies. Lists of likely damages in structures per hazard are also provided by Olsen et al. (2016b) and could be reviewed by PDARs prior to the initiation of the process. Each structure is typically evaluated as a system, as well as by the system components/elements. Note that the PDA described in this report does not refer to any statutory or regulatory requirements.

Predefined structural element damage level descriptions with associated color tagging and example damage photos could be in place to assist inspections. It may be beneficial for lead agencies to adopt the element damage descriptions provided in Olsen et al. (2016b) or further refine them based on their own needs and experience. Geo-tagging of data is important during the procedure, so that the data can subsequently be reported to the central agency repository and integrated within the GIS-based asset management platform available.

3.2.4.3 Data Collection and Reporting

Accurate asset inspection data can ensure that emergency management decisions correctly reflect actual asset conditions post-disaster. The procedure followed by many State agencies in terms of PDA reporting after disaster events involves a substantial amount of field and office work, such as manually completing inspection forms (Olsen et al., 2016a; Reed and Wang, 1993; Alaska Dept. of Transportation, 2014). Following this procedure, the inspection team should carry with them documents containing assets' ID numbers and definitions. Once the inspection is done, the next step involves manual recording of information into the headquarters' digital structures database. Such a procedure, apart from being time-consuming, entails significant opportunities for human errors.

To increase the efficiency and reliability of the PDA reporting process, agencies could use applications (apps) installed on smart devices for data collection instead of inspection forms with manual data entry. Examples include the New York State DOT Road Status and Damage Assessment Tool.[18]

Detailed sample practices on the development of interfaces, basic functions and data structure within such apps for highway systems are suggested in the NCHRP Project 14-29 document "Guidelines for Development of Smart Apps for Assessing, Coding, and Marking Highway Structures in Emergency Situations" (Olsen et al., 2016c). The NCHRP 14-29 document lists the following basic elements for smart reporting apps:

- Existing structures inventories embedded in the app, or the ability to access the asset management database for this information via cloud services.
- Access to hazard data, as these are compiled by the central emergency management platform.
- Access to the assets geo-location.
- Digital forms of the damage levels of the different structural components, along with digital sample photos of each level of damage.
- Photo capture and geo-tagging functionalities to translate photos into geo-tagged imagery metadata that can be incorporated into the structures information at the central asset management database.
- 3G/4G/5G networking and connection to Wi-Fi hotspots.

When communication links are available, compiled inspection data can be transmitted in real time to the agency's central database. When these communication links are not available on site, the PDAR can send the data when communication is reestablished.

A streamlined chain of command between the PDARs and the headquarters of State transportation agencies could prove helpful during PDI operations. Standard work packets could be developed for the PDARs, including specific protocols on the use of the smart apps, contact information, inspection route maps, and information on the chain of command. For example, an Assistant Emergency Manager could ensure the implementation of the standard work packets assigned to the inspection teams including

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[18] https://www.esri.com/news/arcnews/spring10articles/road-status.html.

assessing, coding, and marking procedures. The Assistant Emergency Manager could coordinate and communicate the findings with the headquarters and the PDARs during the time of inspections. The Emergency Data Coordinator (EDC) could ensure that the data transfer protocols are being followed by the PDARs. Further, the EDC could maintain the data quality and share the data in the most useful form for decision-making.

3.2.4.4 Benefits of Developing Standardized PDA Protocols

This study identifies the benefits of standardization in the currently State-dependent PDA forms. The NCHRP Research Report 833, Volume 2, (Olsen et al., 2016a) has already made steps toward that direction, providing readily available PDA form templates for bridges, culverts and tunnels. However, adoption of the forms from State DOTs has yet to be demonstrated at a nationwide level.

State DOTs may prefer a more flexible solution. Instead of template forms, a set of minimum procedures could be established nationwide, guiding State DOT and lead agencies' responders to report basic asset properties (geo-location, structure material, etc.). These procedures could also provide information on checking and scoring specific asset components, such as the bearings, deck, pier, abutments, and expansion joints in the case of bridges. Such procedures could build upon asset semantic and geometric information included in national standards, such as those currently being developed by the ongoing TPF-5(372) project ("BIM for Bridges and Structures"), a collaborative effort of more than 20 States, the FHWA, and the American Association of State Highway and Transportation Officials (AASHTO).[19]

3.2.4.5 Coding and Marking

After the PDA is conducted, Olsen et al. (2016b) suggest that inspected highway structures are marked physically in an obvious location using colored placards that signify the coding option: green for INSPECTED or red for UNSAFE. If a structure is marked UNSAFE during a PDA evaluation, it should be further evaluated via a DDA.

Detailed Damage Assessment

Members of the emergency management group involved in the DDA process may include the EMC, the Managing Engineer, the Assistant EMC, the Chief (structural, geotechnical, hydrological, mechanical, materials) Engineers, the DDA Inspectors, and Office Support Staff (for further details on the ERT composition and contributions refer to section 3.3). Note that the DDA described in this report does not refer to any statutory or regulatory requirements.

During DDA, highway structures may be marked with one of three coding notations on a new/updated placard: INSPECTED, LIMITED USE, or UNSAFE. For further details on the definitions of each posting category, readers may refer to the NCHRP Research Report 833, Volume 3 (Olsen et al., 2016b). This posting allows the State DOT, the field crews and the public to know the condition of the structure, as well as the date and time the assessment was performed. In addition, it could prove helpful if DDAs were conducted for all structures where damage has been indicated as possible, regardless of the PDA outcome, factoring in that structures with an INSPECTED placard have a lower priority than those designated as UNSAFE.

3.2.4.6 Damage Detection Methods

Alipour (2016) surveyed the type of damage detection methods employed by transportation agencies in the United States for the post-hazard damage assessment of bridges. The survey indicated that visual inspection and non-destructive evaluation (NDE) are the most frequently used methods, and that most States still refrain from the usage of emerging technologies. Examples of emerging technologies include Light Detection and Ranging (LiDAR), Interferometric Synthetic-Aperture Radar (InSAR), and aerial

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[19] https://www.bimforbridgesus.com/

imagery. However, visual inspections entail accident risks, are time consuming, and fail to cover certain data needs that would significantly assist subsequent PEI procedures, such as structure movement data, bathymetry data or hydraulic data (Jalinoos et al., 2019).

Depending on the resources available, agencies may rely more on technology-based damage detection techniques that can reduce the risks associated with visual inspections, while simultaneously increasing the accuracy and speed of data collection. Remote sensing technologies, for example, can significantly speed up the procedure, as they are readily available for deployment after the event, which makes them a suitable technique for the collection of perishable field data. Table 3-6 and Table 3-7 provide an overview of the current state-of-practice remote sensing methods, along with their working principles and commonly used payload.

Table 3-6: Space-borne, airborne, and water-based remote sensing devices and commonly used payload.

Group	Technology	Payload
Space-borne	Earth Observation Satellites	InSAR
Airborne	Light General Aviation Manned Aircrafts	Optical LiDAR
		Photogrammetry-focused camera
Water-based	Unmanned Water Systems or Unmanned Marine Vehicles or Autonomous Surface Vehicles (ASV) or Underwater Remotely Operated Vehicles (U-ROV) and Bathymetric Survey Boats	Depth sensor
		GPS with digital compass
		Single- or multi-beam SONAR
		Optical imagery and video
		Interferometric SONAR

Table 3-7: Ground-based remote sensing devices and commonly used payload.

Group	Technology	Payload
Ground-based	Unmanned Aircraft Systems (UAS)	High-resolution camera
		Infrared camera
		InSAR
		Near-infrared LiDAR
		Bathymetric LiDAR
		GPS with Inertial Measurement Unit
		Built-in collision avoidance (optional)
	Stand-Off Remote Sensing (e.g., total stations or high-resolution digital camera; laser vibrometer; Image by Interferometric Survey for Structures (IBIS-FS) placed on a tripod at a certain distance from the highway asset)	(No information)
	Vehicle-Based Technologies	LiDAR
		LDV
		High-resolution camera
		Radar (e.g., synthetic-aperture radar sensor)

3.2.5 Road Closures and Detouring

Following PDA and DDA, agencies may likely need to decide upon route closures and available detours that will allow for the continuity of operations on the highway network. Lead agencies may benefit from incorporating traffic data into the decision-making process, in conjunction with PDA results. The damage assessment information could then be associated with traffic volumes, network capacity, and trip demands. Such an assessment could be performed by qualified traffic engineers, possibly with the aid of optimization algorithms to allow for the optimum re-routing alternative, based on the highway system characteristics.

The network's resulting traffic state (i.e., the sections closed to traffic due to damage and the available detours) may be stored and monitored in GIS format within the central emergency management database. The agency is responsible for informing the public as soon as possible for the disaster-related changes in the network. The latter may be conducted efficiently by loading the updated network condition as a GIS layer into existing map applications.

The outlined procedure could follow a standardized protocol described into the lead agencies' emergency traffic plan.

3.2.6 Communication and Coordination

It is beneficial to establish protocols for intra-agency communications during the FR, PDA, and DDA stages, as well as for the inter-agency communications with Federal, State or local organizations. These protocols should follow the recommendations outlined in chapter 7, Coordination and Communication, of the NCHRP Research Report 833, Volume 2 (Olsen et al., 2016a). Furthermore, the following key parameters may be considered when establishing the associated inter-agency lines of communication:

- Mutual aid arrangements and regulatory responsibilities.
- Establishment of clear interconnections with the community.
- Inter-agency compatibility.
- Development of public-private joint planning and cost sharing agreements.

Table 3-8: Connection of "3.2. PDI Procedures" with the Resilience Evaluation Tool. The adopted PDI procedures increase the score of the following measures up to 4.

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Functionality	Resourcefulness	Organizational	*"Crisis Decision Making"*	*3.2.2. Fast Reconnaissance;* *3.2.3. Rapid Damage/Loss Assessment;* *3.2.6. Road Closures and Detouring*
	Robustness	Socio-economic	*"Direct and Indirect losses"*	*3.2.3. Rapid Damage/Loss Assessment*
	Rapidity	Organizational	*"PDI and PEI Procedures"*	*3.2.2. Fast Reconnaissance;* *3.2.4. Preliminary Damage Assessment;* *3.2.5. Detailed Damage Assessment*
	Rapidity	Socio-economic	*"Volunteering in Event Response Activities"*	*3.2.2. Fast Reconnaissance*
Database, PDI and PEI practices	Data Collection and Management	Organizational	*"Geospatial Visualization"*	*3.2.2. Fast Reconnaissance;* *3.2.3. Rapid Damage/Loss Assessment;* *3.2.4. Preliminary Damage Assessment*

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
	Data Collection and Management	Organizational	*"Automated Decision Making"*	*3.2.4. Rapid Damage/Loss Assessment*
	Data Collection and Management	Organizational	*"Procedures for Unbiased data Collection"*	*3.2.4. Preliminary Damage Assessment*
	Data Collection and Management	Organizational	*"Database Updating Procedures"*	*3.2.3. Rapid Damage/Loss Assessment*
	Data Collection and Management	Organizational	*"Remote Sensing Automation"*	*3.2.2. Fast Reconnaissance; 3.2.5. Detailed Damage Assessment*
	Responders Needs	Organizational	*"PPE and Supplies"*	*3.2.4. Preliminary Damage Assessment*
Adaptability and Operability	Security	Technical	*"Risk Assessment and Scenario Planning"*	*3.2.3. Rapid Damage/Loss Assessment*
	Redundancy	Organizational	*"Equipment Inventories for Response"*	*3.2.4. Preliminary Damage Assessment*
	Security	Technical	*"Screening/Tagging Procedure"*	*3.2.4. Preliminary Damage Assessment*
	Security	Organizational	*"Emergency Response Plans"*	*Entire 3.2 section*
Multi-Level Governance	Communication and Trust	Organizational	*"Communication Methods"*	*3.2.7. Communication and Coordination*
	Communication and Trust	Organizational	*"Communication Language"*	*3.2.7. Communication and Coordination*
	Networks	Organizational	*"Inter-Agency Coordination and Cooperation"*	*3.2.7. Communication and Coordination*
	Networks	Organizational	*"Inter-Agency Compatibility"*	*3.2.7. Communication and Coordination*
	Networks	Organizational	*"Public-Private Joint Planning"*	*3.2.7. Communication and Coordination*

3.3 PDI Team Composition and Qualifications: Emergency Response Team Core Disciplines and Contributions

The PDI ERT composition can follow a structure similar to that presented in the NCHRP Research Report 833, Volume 2 (Olsen et al., 2016a). Several disciplines whose role is auxiliary yet essential to the PDI procedures may be added to the aforementioned composition. Moreover, lead agencies are encouraged to establish a clear chain of command between the ERT members, as per the recommendations of Olsen et al. (2016a). Even with fully developed ERTs and well-established command lines, each person in charge should know in advance their key roles and should have an action plan, contingent upon the particular hazard and its extent.

A lack of cohesion is identified across several State DOTs regarding this matter. For example, the Alaska DOT (Alaska Dept. of Transportation, 2014) includes a detailed description for each role, whereas the New York State DOT (O'Connor, 2010) does not provide any insight on the duties of each member of the emergency personnel. To address this gap, the presented PDI methodology offers following examples of team key members and contributions. Most of the team key members and contributions are directly adopted from the NCHRP Research Report 833. Please note that after carefully reviewed the NCHRP Research Report 833 and other relevant documents, the authors found a few additional roles beneficial to the team's functions.

1. ***EMC***: The EMC may be responsible for the overall coordination and communication in case of an emergency across the entire State DOT. The EMC oversees the State DOT's incident command center and its coordination with external agencies, while being continuously informed about the ongoing PDI procedures. The EMC is expected to have at least 15 years of proven experience in emergency management operations and coordination of emergency procedures, and hold a degree in management and administration, engineering or a related field.

2. ***Managing Engineer*** (ME): The ME may be the leader of the Subject Matter Experts (SME) responsible for making all assessment decisions regarding highway structures. The ME position ideally corresponds to a registered professional engineer with at least 10 years of proven experience in emergency management operations and field inspections.

3. ***Chief Engineers***: Chief engineers may serve as SMEs who coordinate specialty inspectors on structural, geotechnical, hydrological, mechanical, and materials issues. Chief Engineers are responsible for applying the official damage assessment procedures described in the ERP. Chief Engineers are expected to be registered professional engineers with at least 5 years of proven experience in emergency management operations and field inspections.

4. ***Assistant EMC***: The Assistant EMC may be a person that ensures the implementation of the standard work packets that have been developed for the inspection teams. The Assistant EMC is also responsible for the coordination and communication between the headquarters and the field teams during the time of inspections, as well as for the proper communication of findings. The Assistant EMC reports directly to the EMC. At least 10 years of proven experience in emergency management operations and coordination of emergency procedures would be desirable, along with a degree in management and administration, engineering, or a related field.

5. ***EDC***: The EDC is responsible for the establishment and update of data transfer protocols, and the coordination of all digital data. He/she oversees the integration of data collected during the FR, PDA and DDA stages into the central emergency management database and is responsible for the seamless operation of the smart data collection method implemented during the PDA stage. The EDC ensures that data transfer protocols are being followed by the PDARs, while he/she is also responsible for the quality of data, and for providing them in the most useful form for decision-making. The EDC is in close cooperation with the EMC and the ME, while he reports to the EMC. At least 15 years of proven experience in database administration, data analysis and management would be desirable, along with a degree in computer science and information systems or a closely related field.

6. ***Emergency Data Analysts*** (EDAs): The EDAs are located at the agency's headquarters and are responsible for the processing and analysis of data received in the central emergency management database. The EDAs report directly to the EMC. They are expected to have at least 5 years of proven experience in database administration and data analysis and hold a degree in computer science and information systems or a closely related field.

7. ***FRC***: The FRC oversees the entire FR Stage. He/she is responsible for the coordination and communication between the headquarters and the field teams (in the case of manned FR procedures), as well as for the proper communication of findings. The FRC is in close cooperation with the EDC and the ME, while he/she reports to the EMC. The FRC is expected to have at least 7 years of proven experience in emergency management operations, and hold a degree in management and administration, engineering, or a related field.

8. ***Traffic Managers/Engineers***: Traffic managers or traffic engineers are qualified engineers or managers with significant background on traffic analysis. They are responsible for the

implementation of the emergency traffic management plan, including the identification of lifelines, the prioritization of inspection routes, the identification of optimum post-event detours based on PDA results, and the communication of the updated network conditions to the public. Traffic managers/engineers with at least 5 years of proven experience in traffic data analysis and database administration, and a degree in engineering, computer science and information systems or a related field would be considered suitable for the position.

9. ***PDARs***: A PDAR is an individual who will perform PDA evaluations following an emergency event. For Response Level 1, PDARs can be regular inspectors, while for higher response levels, PDARs should be certified emergency responders (e.g., maintenance and operations crews and design engineers). PDARs should receive adequation inspection trainings. Where relevant, PDARs should complete the State DOT's smart data collection app training course.

10. ***DDA Inspectors***: DDA Inspectors are structural inspection teams with significant background and experience for detailed inspection of structures. It is recommended that they are registered professional engineers with a minimum of 6 months of proven experience in field inspections.

11. ***Regular Inspectors***: Regular inspectors are knowledgeable individuals within the agency that have experience performing routine inspection of highway structures.

12. ***Communication/Press Coordinator*** (CC): The CC is responsible for communicating with the public and press from an informational point of view. It is recommended that the CC hold a degree in communications/media or related field and has at least 5 years of work experience as a press coordinator or similar.

13. ***Logistics Coordinator***: The Logistic Coordinator serves as a connection link between the EMC, ME, and the SME team by properly coordinating logistic support for the responders. Four or five years of proven experience on logistics coordination would be desirable, along with a Bachelor of Science or a Bachelor of Business Administration or a related field.

14. Maintenance Managers, Construction Managers, Office Support Staff, Attorneys, Advisors, or other administrative business and regulation specialists.

Table 3-9: Connection of "3.3. Team Composition and Qualifications" with the Resilience Evaluation Tool. The adopted "Team Composition and Qualifications" actions increase the score of the following measures up to 4.

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Database, and PDI and PEI Practices	Responders Needs	Organizational	*"Roster for Emergency Team Members"*	*3.3. Emergency Response Team Core Disciplines and Contributions*
	Responders Needs	Organizational	*"Key Contacts in Authorities"*	*3.3. Emergency Response Team Core Disciplines and Contributions*

3.4 PDI Team Training

Some State DOTs have a well-structured training plan, tailored to the roles of the ERT and recurring at well-defined intervals (Utah Dept. of Transportation, 2017; Oklahoma Dept. of Transportation, 2017; and O'Connor, 2010).

The training framework suggested herein is based on Nakanishi and Auza (2015), yet is updated to reflect the practices of the enhanced PDI methodology. These benefit those in charge of the ERP procedures and methodologies, including key personnel and backup personnel, from local, State, and Federal agencies. Selection of frequency and format of training may reflect the pace of changes in organizational structure and technology.

3.4.1 Training Levels

Audience of various backgrounds and duties may have diverse training demands that may not be addressed by a single set of training materials. Three levels of training are identified from the literature survey and suggested below to address this variation:

1. **High-level training** for employees who will interface with PDARs to some extent (e.g., GIS, IT, or logistics staff), with a suggested annual rate of occurrence.

2. **PDAR training** for personnel designated to perform PDAs, including performance of PDA evaluations, and translating the PDA-stage results to the DDA stage. Training sessions on the use of basic and advanced technologies (smart data collection apps) used during the PDA stage are also within this level. PDAR training could be conducted annually in the form of full-day workshops, while a quarterly-offered 1-hour refresher course is recommended.

   Additional steps to assist the PDARs preparedness prior to an emergency event include (modified from Olsen et al., 2016a):

   - Driving inspection routes (annually).
   - Visiting reporting stations or local offices (annually).
   - Identifying alternative driving routes.
   - Familiarizing with major river crossings (annually).
   - Verifying supplies (quarterly).
   - Performing mock-up exercises on the use of the smart data collection app (quarterly).
   - Training immediately after the event: once an emergency event has occurred and PDAR teams have been assembled, a quick refresher course (approximately half an hour in length) could be given before sending the teams out in the field.

3. **Specialized training** modules for the EMC, ME, EDC and data analysts, chief engineers, traffic engineers, press coordinator, logistics coordinator, and DDA inspectors could be performed annually. The modules could offer an overview of all stages of the emergency response procedures and cross-discipline training, while each of these modules specializes on the specific tasks needed by the corresponding ERT members.

The suggested training sessions are expected to have an interactive format to help ensure the highest level of knowledge, skills, and competencies for the trainees. Alongside traditional methods, lead agencies can consider incorporating interactive training, hands-on training based on potential natural disaster scenarios, workshops on the use of new technology with field exercises, or self-paced training with asynchronous online courses in their training programs.

Considering changes or updates in the agency's organizational structure, and/or the technological tools incorporated in the emergency response procedure, agencies may consider performing exceptional training courses, with the aim of introducing these changes to the emergency group personnel.

3.4.2 Self-Assessment Evaluation Tools

Lead agencies may benefit from incorporating self-assessment evaluation modules within their training programs, to quantify and assess the acquired knowledge by trainees. Self-evaluation tools provide aggregated data on the actual level of education of the ERT members. The results of this assessment can be included in annual training assessments to identify opportunities for improvement of the training material.

3.4.3 Mock Exercises

As per the recommendations of NCHRP (Olsen et al., 2016a), lead agencies may also benefit from including mock exercises in the training procedure. Such exercises have been proven to be an effective means of testing emergency response procedures under non-threatening but realistic conditions with a large sample of the ERT brought together. Given that such exercises are resource-demanding, a frequency of once every four years is recommended in the abovementioned NCHRP report. Following a mock scenario, it may be useful for leadership to meet and discuss the results, address gaps, and propose solutions to come into effect before the next emergency event.

3.4.4 Community Training and Raise of Public Awareness

Lead agencies could offer annual training opportunities to local government representatives in the form of one-day workshops, to ensure the preparedness of the local community in the case of an emergency event. The development of an online public information webpage, where basic features of the adopted lead agency's emergency response practices are communicated to the public in a comprehensive manner, and in multiple language as needed, could also prove helpful.

Table 3-10: Connection of "3.4. PDI Team Training" with the Resilience Evaluation Tool. The adopted 'PDI Team Training' procedures increase the score of the following measures up to 4.

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Database, and PDI and PEI Practices	Training	Organizational	*"Training Availability"*	*3.4.1. Training Levels*
	Training	Organizational	*"Percentage of Staff Trained Last Year"*	*3.4.1. Training Levels*
	Training	Organizational	*"Staff Evaluation During Drills"*	*3.4.2. Self-Assessment Evaluation Tools;* *3.4.3. Mock Exercises*
	Training	Organizational	*"Training Drills for Local Community"*	*3.4.4. Community Training and Raise of Public Awareness*
	Training	Organizational	*"Effectiveness of Training Reinforcement"*	*3.4.2. Self-Assessment Evaluation Tools*
	Training	Organizational	*"Cross-discipline Training"*	*3.4.1. Training Levels*
Multi-Level Governance	Leadership and Culture	Organizational	*"Engagement and Awareness of Staff"*	*3.4.1. Training Levels*
Functionality	Robustness	Organizational	*"Regular Testing of Plans"*	*3.4.3. Mock Exercises*
	Resourcefulness	Organizational	*"Human Resources"*	*3.4.1. Training Levels*

Chapter 4 Post-event Engineering Investigation Suggested Procedures

The current state-of-practice for PEI procedures includes field reconnaissance missions that occur within hours or weeks of an extreme event following a PDI. The objectives of reconnaissance missions include the following:

- Documenting the performance of various highway infrastructure asset typologies.
- Focusing on assets that sustained some level of damage or those that totally failed.
- Reporting and disseminating lessons learned from the extreme event to multiple stakeholders.
- To some limited extent, uncovering and highlighting needs for existing analysis, design, and construction codes and specifications to be modified or enhanced based on lessons learned.

In this chapter, PEI is perceived as a holistic framework that aims at supporting the overarching goal of improving resilience in transportation infrastructure. This enables well-prepared PEI actions across various government and academic participants. The findings can therefore support both scientific advancement and decision-making process. For the main goal of PEI endeavors to be achieved, four specific objectives are identified:

- Integrate resilience thinking into the asset management lifecycle.
- Integrate physical risks into investment decision-making.
- Facilitate quick disaster recovery.
- Improve designs and practices to avoid recurring damages and losses.

These objectives may be materialized with the help of a robust action plan that outlines a series of action items for each of the four objectives of the suggested PEI objectives (Figure 4-1). Building upon the main goal and specific objectives of the PEI Enhanced Methodology, this chapter presents suggestions that cover:

- Field reconnaissance missions that take place either after the PDI procedure has concluded, or in parallel with the PDI activities, in case perishable disaster-related data should be quickly collected.
- Data collection, processing, and interpretation methods that aim at informing robust decisions on network-level rehabilitation (post-event), or network-level strengthening namely, prioritization of asset upgrade (pre-event).
- Long-term resilience-building strategies where all data and decisions are aggregated to enhance the resilience and preparedness of highway networks.

Chapter 4 follows the PEI steps in a linear fashion beginning from the short-term disaster response (field reconnaissance missions and immediate network repairs) and concluding with the long-term planning for network resilience. Each suggestion links to the RET of chapter 2, and the relevant indicator, dimension, lens and pillar.

The PEI procedure presented in this chapter may be used as a standalone methodology. It may also be used in conjunction with the PDI methodology described in chapter 3. This will allow for the activation of certain PDI/PEI synergies, thus maximizing the efficiency of implemented actions, while reducing associated costs and resources.

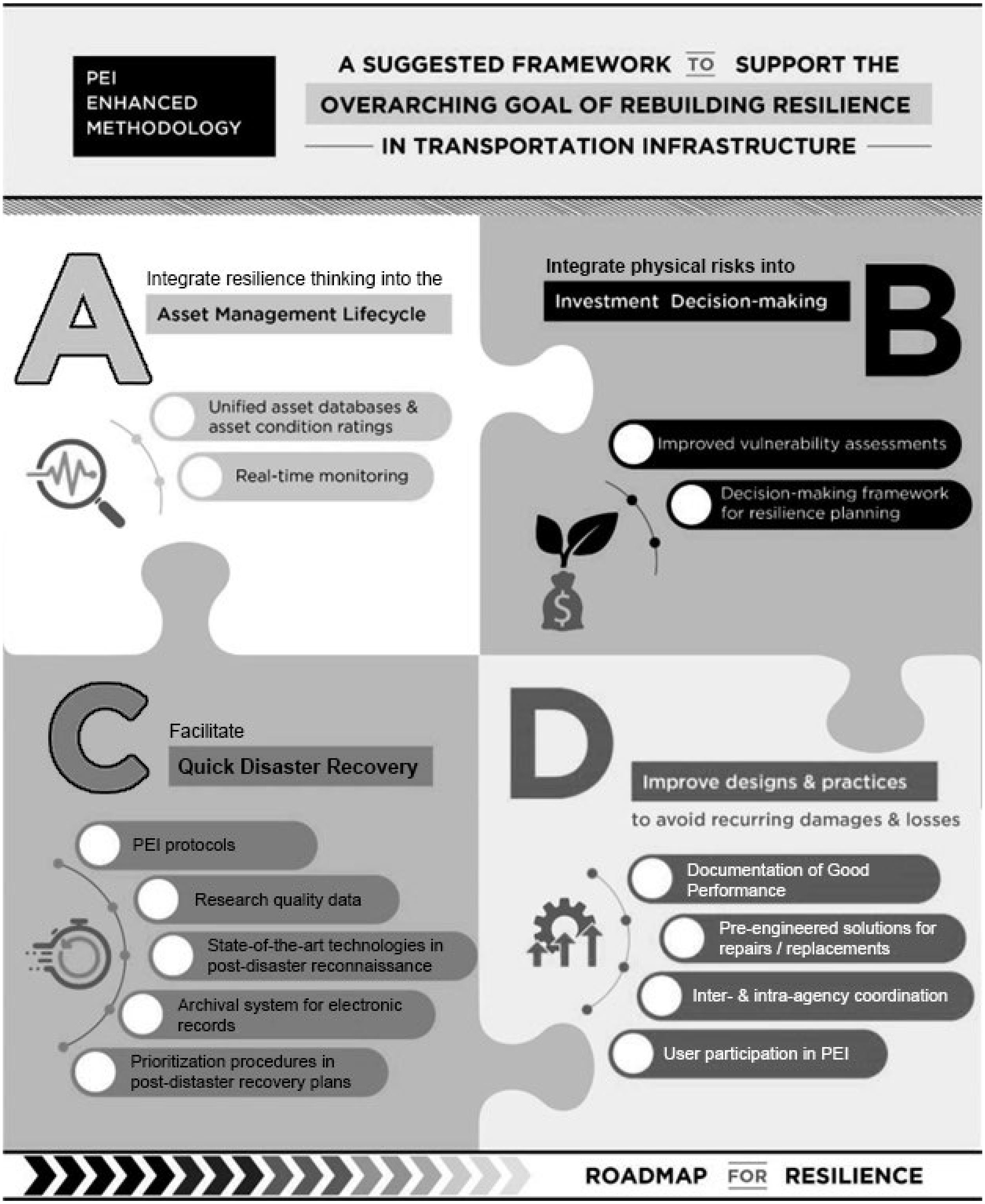

Figure 4-1: PEI specific objectives and suggested action items (image by the authors)

4.1 Field Reconnaissance Missions and Post-event Data Collection

4.1.1 Active Involvement in Reconnaissance Missions

Several associations have developed and currently use PEI practices tailored to field reconnaissance missions and data collection. Examples include the American Society of Civil Engineers (ASCE), the Multidisciplinary Center for Earthquake Engineering Research, the Earthquake Engineering Research Institute (EERI), the FHWA, the Geotechnical Extreme Events Reconnaissance (GEER), or the Structural Extreme Events Reconnaissance (StEER).

Overall, such practices are hazard-specific, and, as with the case of existing PDI procedures, most of them are targeted to earthquake hazard. It is common practice for the global engineering community to rely on case studies of structures that underperformed during an extreme event. The underperformance can be due to design defects, construction malpractice, or the fact that the design codes which were followed at the time did not account for an extreme event of such magnitude. Notwithstanding the lessons learned from the reconnaissance studies of the past, there is still space for further improvement in terms of data quality and systematic documentation. This section provides enhanced methods and techniques toward this direction.

Suggestion 1: Create PEI field reconnaissance mission frameworks for all hazards on a Federal or State level.

The creation of a central interdisciplinary association on a Federal level for oversight of field reconnaissance missions is suggested, as well as, the collection of all the gathered data and information on a central database. Similar endeavors are that of the National Science Foundation Extreme Events Research Networks,[20] also referred to as Extreme Events Research Interdisciplinary Science and Engineering, and that of DesignSafe[21] cyberinfrastructure, the web-based research platform of the National Science Foundation Natural Hazards Engineering Research Infrastructure. Both endeavors are research-oriented but could serve as a baseline for a Federal-level interdisciplinary association to overview field reconnaissance missions. Trigger criteria for various levels of actions may be defined by the respective lead agencies depending on the vulnerability of the network considered.

Information transfer from PDI teams to the association can assist the procedure**.** Given that PEI is time-sensitive, PDI teams should communicate the gathered data related to highway asset accessibility, road closures and detours. The PDI teams should also provide suggested routes to the PEI field reconnaissance teams. It would be helpful if PDI teams also provided the association with a database of the assets and their coordinates, ideally summarized in a GIS-based platform. The latter would largely facilitate critical decisions in terms of: PEI prioritization, as some data may perish sooner due to natural processes or immediate repairs for traffic restoration; PEI organization, specifically decisions about the delivery of team members into routes and assets; and post-event network rehabilitation. After the main PDI findings have been communicated to the association, the latter may activate a PEI field reconnaissance team, similarly to the procedure followed by the GEER Steering Committee, where a mission leader is identified (*Manual for GEER Reconnaissance Teams, v.4*, 2014). The PEI field reconnaissance team may comprise both State DOT or lead agency's members and members of the global scientific committee who are willing to visit the hazard-impacted location and study the infrastructure performance and the response of the affected communities. Lead agencies may benefit from assembling a predefined PEI field reconnaissance team at the State level, for disaster planning and preparation purposes. An indicative team organization structure is outlined in section 4.4.7.

The central interdisciplinary association could adopt the management of many hazards, both in a multi-hazard fashion (e.g., assets exposed to more than one hazard), and with focus on less frequently

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[20] https://converge.colorado.edu/research-networks

[21] https://www.designsafe-ci.org/#learning

documented hazards (in comparison to earthquakes) and their impact on infrastructure, such as climate change-induced hazards.

At a regional level, not all hazards will necessarily be managed, but emphasis will be placed on those of significance to the area. To this end, a nationwide, high-level framework for field reconnaissance missions relevant to all probable hazards which may be adopted and refined by State/local agencies for pertinent hazards could improve the course of action during future PEI missions.

Suggestion 2: Create detailed suggested procedures for PEI field reconnaissance missions for all hazards.

Detailed suggested practices for field expeditions, in the context of PEI field reconnaissance missions are a prerequisite of well-organized, and properly performed PEIs. Such practices can serve as Quality Assurance/Quality Control, and standardize the PEI field reconnaissance procedure, team organization, and the purpose and role of field activities. Useful documents in these practices may be found in the following (non-binding) manuals:

- "Manual for GEER Reconnaissance Teams" (*Manual for GEER Reconnaissance Teams, v.4*, 2014).
- "Learning from Earthquakes (LFE) Program – Operations" (*Learning from Earthquakes (LFE) – Operations, v.2*, 2015).
- "Guidelines for Failure Investigation" (Barrow et al., 2018).

Further, a PEI field reconnaissance manual can include the following:

1. The goals of the PEI team, including (1) surveying the damaged highway assets, (2) documenting key sites leading to the development of well-documented case histories, and (3) investigating gaps in knowledge for future work and research.
2. Team member composition, organizational structure with communication and command chain, and key roles of each member. The qualifications of the team leader may include knowledge of the field of expertise (academic education prerequisites, State licensure as a Professional Engineer, possible professional certification in one or more fields of technical knowledge, participation in engineering professional societies in the practice of interest, significant experience in one or more technical fields) and qualities of character (objectivity, confidentiality, impartiality and integrity, communication skills). The selection of the team leader is explained and elaborated, along with the key role and contributions of this position. The basis for the selection of the team members, and other collaborators or investigators is clearly outlined.
3. Mission coordination and steps. Such steps are described in detail in the suggested "Manual for GEER Reconnaissance Teams," where the observational focal-points for the reconnaissance effort are organized under (1) context, (2) demand, (3) effects, and (4) tools. The format and timeline of the field meetings are meticulously prescribed, and safety issues are defined, thereby cultivating a culture of safety. Particular suggestions are made on the use of smartphones and social media, note-taking, the use of GPS, geo-referencing practices, site naming conventions, field photography techniques, the use of specialized reconnaissance tools (e.g., ground-based LiDAR, Shear Wave Velocity measurement equipment, UAS photographic drones, etc.), and reporting. The PEI field manual can also draw the inspector's attention on (1) observations and measurements included in the PDI endeavors, for reasons of cross-validation and enrichment of the PDI collected data, and (2) points of lesser structural, yet higher socio-economic importance, such as the damage condition of the surroundings of a damaged bridge, to more rapidly inform repair and rehabilitation activities.

4. Pre-mission planning protocol. As with pre-event planning in PDI, an action plan should be in place prior to the PEI field mission, including the communication line from the impacted area, on a State level, to the Federal level, and from that to the local PEI teams; potential conflicts with the PDI teams; preliminary research needs, in the form of desk studies; scope of work and staffing; budget estimates; initial documents or other data sets or research material to be collected (e.g., from the PDA study, especially if it is documented in a digital platform, which can be easy to access and study; or from past similar disasters).

5. Data collection framework during the site visit, supplemented by further investigation needs (e.g., lab testing of field specimen), and data reporting and interpretation framework.

The quality of the field reconnaissance mission depends on the data that will be collected and eventually summarized in a PEI dataset. Hence, data collection and manipulation are important components of a PEI field reconnaissance manual and are covered in detail in the following subsection.

4.1.2 Data Collection from Field Missions

Data are the raw material that PEI teams collect, organize, review, and analyze to acquire meaningful information. Data are usually gathered by measurements, observations, testing, or analysis, or from documents, research, or interviews (Barrow et al., 2018). In particular, measurements and observations can be taken by physically visiting the damaged highway asset with remote observation techniques. This may include UASs, Unmanned Marine Vehicles, or stand-off remote sensing (e.g., Total Stations or sensors placed on a tripod at a certain distance from the highway asset). A hybrid approach where the PEI teams approaches the damaged asset, but all measurements and observations are taken with remote technology is also possible. The use of GPS units in the field is suggested to locate all recorded information, photographs, and data observations with latitude and longitude coordinates (*Manual for GEER Reconnaissance Teams, v.4*, 2014).

Enabling the standardization of measurement and reporting practice in reconnaissance missions is one of the main goals of the (non-binding) “Manual for GEER Reconnaissance Teams” (*Manual for GEER Reconnaissance Teams, v.4*, 2014). The following suggestions build on this manual while overcoming existing gaps in the use of emerging technologies and digital reporting of the acquired field data.

Suggestion 1: Utilize emerging technologies for data collection.

Recent advances in space-borne, airborne, ground-based, and water-based technologies have significantly enhanced the potential of post-disaster reconnaissance missions (Stone et al., 2017). State-of-the-art instrumentation and mobile data collection applications have significantly aided the teams in capturing quickly perishable data in post-disaster settings (Wartman et al., 2020). Emerging technologies can now be readily incorporated in PEI data collocation protocols, especially in the following domains:

- Rapid mapping with airborne sensing systems.
- Crowdsourcing to capture social science data.
- Omnidirectional imagery (such as those used by Google Maps vehicles to provide a virtual “walk through” of traffic networks globally).
- Geomatics.
- Site characterization with geophysical techniques and on a post-processing level.
- IT.
- Data management and visualization.

Data collection across temporal, geospatial, and social scales, and data integration across different data types and disciplines comprise major challenges for a rigorous PEI decision-support framework. Emerging technologies may accelerate data collection with enhanced safety considerations and enable integration, interoperability, and interconnectivity across different data collection devices. For these reasons, emerging technologies are a vital component of a PEI data collection protocol.

Suggestion 2: Standardize data collection protocols and identify objectives for the collected field reconnaissance data.

Given the digital transformation of the infrastructure construction and post-disaster management industries, some lead agencies may adopt emerging technologies more quickly than others. Variables may be related to the existing infrastructure, and budget availability to acquire new equipment and train the key personnel to operate it, among others. Given the important functions of the collected data, objectives for data collected during field reconnaissance missions should be identified. For example, damage data lists pertinent to different hazards and asset types with associated levels of desirable accuracy could be adopted.

Lead agencies may invest in GIS platforms that aggregate all PDI and PEI data for cross-validation, collective utilization, and exploitation toward lessons learned and code upgrades. This approach can be of value, as damage assessment data and engineering investigation data are combined and can jointly inform rehabilitation decisions. Data visualization on a GIS-based and ideally on a web-based platform could benefit the PEI data collection by accelerating data dissemination while enabling the smooth incorporation of future Internet of Things (IoT)-based features once available. Moreover, many capabilities of the emerging technologies, such as the construction of 3D photorealistic models, or orthophotos assembled by UAS imagery, cannot be fully exploited without GIS infrastructure in place.

Suggestion 3: Document performance intended by design or exceeding expectation.

Existing reconnaissance reports focus on damage reporting, while limited examples of documentation for performance as intended are currently available in reconnaissance missions. When assets display better performance than what was initially evaluated via pre-disaster assessments, agencies should engage in further investigations to determine the reasons behind such behavior and validate the observed reconnaissance outputs.

Conclusions from this process can be useful for updating predictive computational models or modifying existing design practices. For example, earthquake risk assessments have rarely enough geotechnical data to provide realistic predictions of the behavior of geotechnical systems. The systematic documentation of geotechnical case histories in major disaster events could provide valuable insights, especially with respect to liquefaction and fault rupture effects.

If an agency chooses to use the RET, to evaluate the benefit from post-event actions, specific advantages can be quantified for items listed in Table 4-1.

Table 4-1: Connection of the "4.1. Field Reconnaissance Missions and Post-event Data Collection" with the Resilience Evaluation Tool. The adopted procedures increase the scale of the following measures.

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Functionality	Robustness	Technical	*"Asset/System Condition"*	*4.1.1. Active Involvement in Reconnaissance Missions*
	Robustness	Technical	*"Effective Maintenance"*	*4.1.2. Data Collection from Field Missions*
	Robustness	Technical	*"Reconnaissance Tools and Technology"*	*Entire Section 4.1*
	Robustness	Technical	*"Data Visualization, GIS"*	*4.1.2. Data Collection from Field Missions*
	Rapidity	Organizational	*"Rapid Contracting Mechanisms"*	*Entire Section 4.1*
	Rapidity	Organizational	*"Automation (unmanned) Technologies"*	*4.1.2. Data Collection from Field Missions*
	Rapidity	Socio-economic	*"Volunteering in Event Response Activities"*	*4.1.1. Active Involvement in Reconnaissance Missions*
Adaptability and Operability	Security	Technical	*"Data Access Alternatives"*	*4.1.2. Data Collection from Field Missions*
Multi-Level Governance	Responsibility	Organizational	*"Organizational Structure"*	*4.1.1. Active Involvement in Reconnaissance Missions*
	Responsibility	Organizational	*"Knowledge Transfer and Succession Planning"*	*4.1.1. Active Involvement in Reconnaissance Missions*
Database, and PDI and PEI Practices	Data Collection and Management	Organizational	*"Procedures for Unbiased Data Collection"*	*4.1.2. Data Collection from Field Missions*
	Data Collection and Management	Organizational	*"Successful Performance Case Histories"*	*Entire Section 4.1*
	Data Collection and Management	Organizational	*"Database Updating Procedures"*	*4.1.2. Data Collection from Field Missions*
	Data Collection and Management	Organizational	*"Data Monitoring Frequency"*	*4.1.2. Data Collection from Field Missions*
	Data Collection and Management	Organizational	*"Automated Decision Making"*	*Entire Section 4.1*
	Data Collection and Management	Organizational	*"Remote Sensing Automation"*	*4.1.2. Data Collection from Field Missions*
	Data Collection and Management	Organizational	*"Information Backup"*	*4.1.2. Data Collection from Field Missions*

4.2 Post-event Network Rehabilitation

The reconstruction of damaged highway assets should involve repairs of critical elements to a basic operational level as soon as possible. Lead agencies could establish ex-ante rehabilitation mechanisms and financial arrangements within their pre-event recovery plans to rapidly initiate repairs after a disaster, allowing for cost-effective reconstruction solutions (Fengler et al., 2012).

It is also suggested that lead agencies take advantage of the results provided by rapid response tools with a loss estimate module for an initial pre-evaluation of repair needs and costs before the outcome of the PDI and specialized engineering investigations are made available. Based on this pre-evaluation, agencies may drive preliminary estimates regarding the needed rehabilitation funding and initiate procedures to secure it.

Accurate damage documentation from the PDI phase can reduce the need for further engineering investigations prior to the decision to make repairs. Moreover, the existence of efficient repair prioritization algorithms and accelerated construction methods based on pre-engineered solutions can assist the recovery process.

4.2.1 Accelerated Reconstruction

Lead agencies may refer to the relevant NCHRP studies (Blanchard et al., 2009; Keck et al., 2010; Lockwood et al., 2005) for practices on emergency accelerated reconstruction processes and disaster recovery. Such practices span from contract management to ensuring fast mobility of repair teams and flexibility in design based on the availability of materials. Such practices can be considered for being outlined within the agencies' short-term network rehabilitation plans.

Furthermore, lead agencies may benefit from developing and including lists of pre-engineered solutions per damage/hazard within post-disaster repair plans. Such solutions may include both of the following:

- Prefabricated components that are easy to erect, assemble and transport, thereby allowing for the rapid restoration of traffic in critical lifelines (temporary measure).
- Existing repair solutions for different structural typologies under the hazards of interest. Pre-engineered solutions can accelerate the immediate repairs while increasing efficiency in terms of costs and performance.

Lead agencies should be cooperative and should engage other agencies and expert consultants during the pre-planning phase for the compilation of easy-to-implement repair solutions lists. Furthermore, the existence of rapid contracting mechanisms is suggested to mobilize contractors and construction equipment as quickly as possible through fast-tracked selection process and contract signing. Similarly, pre-event agreements with provider companies would ensure availability of prefabricated structural components.

4.2.2 Repairs Prioritization

Efficient repair prioritization strategies can result in faster network recovery time and proper allocation of reconstruction funds. Lead agencies should incorporate prioritization systems compatible with their readiness level.

Possible solutions to the prioritization problem range from state-of-the-art optimization algorithms (Chen and Tzeng, 1999; El-Anwar et al., 2016; Karlaftis et al., 2007; Orabi et al., 2009) to more simplistic and computationally efficient methodologies. Optimization algorithms provide optimal repair funding allocation under a number of prioritization criteria and a given constraint (typically the available budget). On the other hand, more simplistic methodologies, such as scoring systems based on a number of evaluation criteria, are easier to implement, yet do not always provide optimal results.

Criteria that may be incorporated within repair optimization algorithms include damage level/asset condition or rating, importance of damage link, traffic disruptions, network functionality, asset reconstruction cost, and difficulty of repair work.

In addition to these criteria, the most common constraints in the optimization process include budget, project deadlines, and available personnel.

The implementation of the above suggestions can lead to the increase of the score of different measures in the RET, as can be seen in Table 4-2.

Table 4-2: Connection of the "4.2. Post-event Network Rehabilitation" with the Resilience Evaluation Tool. The adopted procedures increase the scale of the following measures up to 4.

Pillar	**Lens**	**Dimension**	**Measure**	**Reference to relevant Methodology Subsection**
Functionality	Robustness	Technical	*"Upgrade Plans"*	*Entire Section 4.2*
	Robustness	Technical	*"Pre-engineered Solutions"*	*4.2.1. Accelerated construction*
	Resourcefulness	Organizational	*"Pre-event Recovery Planning"*	*4.2.2. Repairs Prioritization*
	Resourcefulness	Organizational	*"Availability of Construction Equipment"*	*4.2.1. Accelerated construction*
	Resourcefulness	Organizational	*"Availability of Construction Materials and Means"*	*4.2.1. Accelerated construction*
	Rapidity	Organizational	*"Rapid Contracting Mechanisms"*	*4.2.1. Accelerated construction*
	Rapidity	Technical	*"Prioritization Criteria"*	*4.2.1. Accelerated construction*
Database, and PDI and PEI Practices	Data Collection and Management	Organizational	*"Automated Decision Making"*	*4.2.2. Repairs Prioritization*
Adaptability and Operability	Mobility	Technical	*Post-event Level of Service (LOS)*	*Entire Section 4.2*

4.3 Disaster Data Processing

PEI disaster data processing is comprised of the following:

- Data collection.
- Data preparation/clean-up (redundant, incomplete, or incorrect data are eliminated).
- Data input (cleaned-up raw data are translated into a language with which data analysis can be conducted).
- Processing (data are processed for interpretation, employing machine learning algorithms, with supervised or unsupervised learning methods, depending on the expected outcome of the data set).
- Data interpretation (data become readable to non-data scientists with visualization techniques).

- Data storage (processed data are stored for future reference, along with their metadata and dependencies, if any).

Proper data storage is a prerequisite for rapid and easy access by all PEI community members. High Performance Computing, Cloud Computing, and Learning Theory may become the main contributors to the next generation of disaster data processing, and be capable of delivering data of higher accuracy and in greater speed. Novel machine learning algorithms may also enable exploration of more complex data structures.

This section suggests methods and techniques for disaster data processing methods that may yield high-fidelity datasets.

4.3.1 Digital data registration and processing methods

Lead agencies may adopt high-tech UAS- and sensor-based data collection protocols, as well as smart apps and digital data gathering devices. Digital data collection and registration are not necessarily a prerequisite for digital data processing, but largely facilitate the process, especially in the case of interconnectivity between the data collection devices and data processing centers.

4.3.2 Deployment of a Big Data platform to act as a disaster summary database

Collecting multi-disciplinary data in a central database is challenging due to the different collection and reporting methods used across the different disciplines. These methods range from paper-copy forms to fully interoperable digital formats. Digital registration methods should be used to improve disaster data processing, interpretation, and management. In addition, Big Data frameworks and platforms should be implemented.

4.3.3 Electronic archival systems

To enable the long-term retention and storage of the vast amount of network data gathered ex-ante and ex-post a disaster event, State DOTs should have access to in-house or third-party electronic archival systems. A well-designed electronic storage system enables transportation agencies to cope with the new information acquired during field reconnaissance missions, while also retaining existing data and allowing for the easy retrieval of both.

PEI frameworks, customized per the needs of each State DOT, should touch upon disaster-related data archiving objectives, including ways of applying descriptive metadata, ways of characterizing the data to be moved, retention time frames, criticality of information, or other parameters.

Table 4-3: Connection of the "4.3. Disaster Data Processing" with the Resilience Evaluation Tool. The adopted procedures increase the scale of the following measures up to 4.

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Functionality	Resourcefulness	Technical	*"Reconnaissance Tools and Technology"*	*Entire Section 4.3*
Multi-Level Governance	Communication and Trust	Organizational	*"Cross-sector Asset Management Databases"*	*4.3.2. Big Data platform;* *4.3.3. Electronic archival systems*

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
Database, and PDI and PEI Practices	Data Collection and Management	Organizational	*"Procedures for Unbiased Data Collection"*	*4.3.1. Digital data registration and processing methods*
	Data Collection and Management	Organizational	*"Automated Decision Making"*	*4.3.2. Big Data platform;* *4.3.3. Electronic archival systems*

4.4 Long-term Resilience-Building Strategies

4.4.1 Collection of Baseline and Post-Disaster Data

Agencies may benefit from collecting both baseline and post-disaster data relevant to the network performance and using them collectively as a roadmap to decide upon the best allocation of resources during post-event recovery planning. Baseline data refers to any information available prior to the occurrence of a disaster, while post-disaster data are collected in the aftermath of a disaster. Naturally, post-disaster information changes with time and should be collected at multiple points to monitor the evolution of network recovery (Horney et al., 2018).

Apart from physical condition data and traffic information, lead agencies could develop a broader database for resilience, comprising damage and non-damage data relevant to the performance assessment of the network ex-ante and ex-post disaster events. See chapter 5 for a detailed description of data collection needs and protocols for assembling the Database for Resilience.

4.4.2 Network Strengthening Plans

Network strengthening plans can eliminate service disruptions during and after natural hazard events. Since strengthening all highway infrastructure assets to targeted safety levels is not possible given limited resources, pre-disaster investments should follow a prioritization mechanism. Efficient prioritization of strengthening actions leads to the selection of a subset of critical assets qualifying for retrofit and demonstrates an explicit linkage to the expected network performance (Peeta et al., 2010).

The FHWA Vulnerability Assessment Framework (Filosa et al., 2017) can be applied in the context of prioritization of long-term strengthening actions against the range of natural hazards that may threaten a transportation system (Table 4-4).

Table 4-4: Step-by-step approach for the prioritization of long-term strengthening actions following FHWA Vulnerability Assessment Framework (Filosa et al., 2017).

Step	Action
1	Articulate objectives and define the strengthening scope
2	Obtain asset data
3	Obtain hazard data
4	Assess vulnerability
5	Identify, analyze, and prioritize strengthening options Perform cost-benefit analysis for the investment alternatives
6	Employ assessment results to inform decision-making and unlock Federal funding mechanisms

Suggested steps for the vulnerability analysis and prioritization procedure follow.

4.4.2.1 Network Vulnerability Analysis

Characterization of the network's vulnerabilities and threats, along with the expected functionality loss, forms a core element of long-term resilience-building strategies. Depending on the problem, its scale, and the targeted resolution of the results, lead agencies may choose among probabilistic or deterministic (scenario-based) methodologies to assess network vulnerability under a potential disaster event.

Probabilistic frameworks are based on the use of asset fragility curves and entail an inherent degree of uncertainty in the identification of the asset damage. This uncertainty stems from the characteristics and reliability of the data set from which the fragility curves were generated. Agencies that have not developed State-specific fragility models for the hazards of interest, should conduct thorough research before employing any of the available fragility models to ensure compatibility and reliability of results.

Probabilistic frameworks yield probabilities of exceedance for a number of discrete damage states, usually ranging from “no asset damage” to “asset failure.” Agencies may translate the probability distribution among these damage states for each portfolio asset into a unique Characteristic Damage Level (CDL) to obtain results that will facilitate the decision-making process. Indicatively, the CDL could be defined as the damage level at which the cumulative probability of exceedance (“P”), is higher than a certain prescribed percentage (e.g., 20 percent) at a given level of hazard. Initializing from the last damage state, the probabilities of damage are added up to the damage state where “P” is higher than the prescribed percentage.

Alternatively, agencies may use deterministic, performance-based methodologies for the vulnerability assessment of assets under various hazard scenarios. Deterministic performance-based frameworks treat the probability of an event as a discrete value, which is computed using a specific hazard assessment framework. To this end, structural damage and/or associated loss are evaluated under a single disaster scenario with known input values, thereby providing stakeholders with finite pieces of information that act as decision-support guides on the planning of asset strengthening. Such a deterministic approach has been adopted by Caltrans (Werner et al., 2006) to assess the seismic risk of the agency's bridges under different earthquake scenarios (using the REDARS 2™ software). The latter corresponds to single earthquake events caused by the rupture of a predefined fault. Mean values of all variables are used throughout the analysis. The spatial distribution of ground shaking (at a specific distance from the fault projection) is provided in the form of peak ground or spectral accelerations at a specific period, calculated by means of ground motion prediction equations embedded in the software. The estimation of damage states in the model is based on the development of an equivalent pushover capacity spectrum for each of the identified bridge classes.[22] The capacity spectrum is then employed for the definition of the spectral acceleration capacities corresponding to each damage state. By comparing the earthquake's demand spectral acceleration to these spectral acceleration thresholds, the damage state of the bridge (to the specific earthquake scenario) is obtained.

4.4.2.2 Prioritization Process

Prioritization procedure could assist highway agencies in strengthening investments and justifying Federal funding. Such a procedure should merge the risks stemming from extreme natural events to the output of asset management optimization processes that comprise the current state of practice for funding allocation of preventive maintenance activities across U.S. highways.

The selected method and associated criteria may be developed and implemented at a State DOT level and are largely dependent on the agency's maturity level, available resources, and hazards of interest. A set of practices that may be helpful is suggested below.

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[22] For a capacity spectrum description, readers may refer to the Capacity Spectrum Method (Freeman, 1998) as this is suggested in ATC-40, as well as to several modifications of the original procedure, such as the Adaptive Capacity Spectrum Method developed by Casarotti and Pinho (2007). Their use is not required by Federal law.

The methodology described in this document uses ***optimization algorithms*** (e.g., Genetic Algorithms, Mixed Integer Linear Programming, Analytic Hierarchy Process, Network Analysis, etc.) as the most accurate prioritization tool for assessing the technical resilience of the network only for lead agencies that display the appropriate maturity level to undertake the task. The criteria that should be considered during prioritization of strengthening strategies span across several aspects of resilience: economic, technical, organizational, and social. As a result, multi-criteria optimization algorithms demand significant computational effort, high technical skills for implementation, and a large amount of data sets. While being very useful in assessing the technical network resilience from a financial perspective, such algorithms display limited flexibility for adaptation to a wide range of situations and limited assistance in wider organizational resilience assessments (Bush et al., 2012).

In any other case, simpler prioritization tools are suggested, with ***scoring systems or indicator-based methodologies*** considered as the most appropriate alternative, such as the RET outlined in chapter 2, the U.S. Department of Transportation Vulnerability Assessment Scoring Tool,[23] or the methodology developed by the World Bank for the Japan Road Transport System (Marcelo et al., 2018). Despite their simplicity, scoring methods are systematically used for resilience assessments due to the following:

- Their inherent customization flexibility and ease of implementation.
- Their transparent and informative evaluation process (that may be easily understood by non-experts).
- Their ability to manage multi-parameter assessments without exponentially increasing complexity and computational effort.

Instead of indicator-based methodologies or scoring systems, lead agencies may perform ***cost-benefit analyses*** for the adopted strengthening alternatives, similar to that suggested by the National Institute of Standards and Technology (NIST) Economic Decision Guide Software,[24] for prioritization of rehabilitation strategies and investments. Via cost-benefit analyses, resilience-related benefits, and costs stemming from competing projects alternatives can be compared with one another or to the status quo ("do nothing" condition) in monetary terms (i.e., Net Present Value or Return on Investment). The method enables the determination of the best (most cost-effective) alternative among several pre-determined options; however, it does not necessarily lead to optimum solution selection.

4.4.3 Lifecycle Instrumentation and Monitoring

Instrumentation and lifecycle monitoring can ensure the long-term resilience of transportation assets. In view of the falling cost of sensor technology, lead agencies may install sensing networks, either wired or wireless, and local or distributed (e.g., Distributed Fiber Optic Sensors), on critical highway assets, to allow for the collection and storage of "live" structure data. Structural Health Monitoring (SHM) techniques are broadly used today in Operations and Maintenance for damage detection, structural capacity evaluation, remaining service life estimation, and slope stability and deformation assessment (Seo et al., 2016). Despite being orders of magnitude quicker than human-based PEI endeavors, the installation of an extended SHM system may become tedious and costly, as it involves the deployment of a dense network of sensors at the granular level of each highway structure of interest (Alzughaibi et al., 2019). An alternative could be the installation of a manageable grid of sensors (e.g., seismometers) in selected locations, complemented by low-cost, low-quality crowdsourcing data. This will allow for hazard intensity estimates at a local scale (or even at an asset scale) that will enhance the accuracy of damage assessments, and overall facilitate the efficient implementation of the PDI/PEI practices.

It is possible that in a few years, infrastructure-sensing-based PEI will become the norm, as the cost/benefit ratio of such systems may justify the strategic selection of dense sensing networks to

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[23] https://toolkit.climate.gov/tool/vulnerability-assessment-scoring-tool-vast

[24] https://www.nist.gov/services-resources/software/edge-economic-decision-guide-software-tool

optimize data collection for PEI purposes. However, all the data collected from field reconnaissance missions, with any available sensing data from pre-installed sensors may be combined with present technology. The effective use of sensing data has many objectives, including cross-validating models constructed with different classes of data (from field mission or from pre-installed sensors), reducing uncertainties, better informing models and expand the PEI databases, and calibrating numerical models or physically testing models with damage-related data from such sensing networks. A rich repository of well-documented damage cases could increase the accuracy of numerical models. Therefore, incorporating infrastructure sensing data originally targeted to lifecycle assessment of the highway structure can be considered in development of PEI data collection protocols.

4.4.3.1 The significance of Internet of Things in SHM techniques

As with the standardization of data collection methods (see section 4.1), the transition to IoT-compatible techniques is a prerequisite in the lifecycle instrumentation of highways assets. One of the most promising prospects of IoT is the comparatively simple collection of vast amounts of data. However, seamless data access is hindered through several traits. First, the data comes from different sources and is heterogeneous, it is unstructured and without clear semantics. Without pre-processing, the data is not interoperable in the first place. Second, the large number of devices causes a mentionable amount of data that needs an annotation with metadata to make it reusable. Finally, the flexibility of IoT devices allows the collection of data at different points in time at different places offering spatial-temporal correlations.

The Open Geospatial Consortium has recognized these challenges and developed the SensorThings Application Programming Interface. The SensorThings Application Programming Interface is a non-proprietary, platform-independent, and perpetual royalty-free standard for the collection, storage, and retrieval of time-series data that provides a geospatial-enabled and unified way to interconnect IoT sensors or other devices, data, and application, over the web. It complements the existing IoT networking protocols, and as an Open Geospatial Consortium standard it allows easy integration into existing Spatial Data Infrastructures or GIS. Therefore, next-generation SHM lifecycle monitoring and disaster-targeted sensors should be incorporated into such global and interconnected protocol for data access to be streamlined across different States or even countries.

A detailed description of available instrumentation and monitoring options per hazard and/or highway asset is provided in chapter 5.

4.4.4 Intra-agency Engagement and Training

In order to ensure efficient implementation of new tools and strategies, agencies should create awareness among all stakeholders on the need for resilience and what this effort entails (El Nakat, 2015). Regular training sessions could help establish a resilience culture within lead agencies. Such sessions would aim to inform key personnel on the established PEI procedures, as well as the agency's long-term strategic plan for resilience. The potential training sessions could be separated into three distinct classes:

- *High-level Training on Resilient Practices*: People working within the department become aware of and aligned with the State DOT's resilience goals. Good practices are highlighted, and internal communications are strengthened via open conversations in order to cultivate personal responsibility regarding the adopted plans and drive resilient behavior.

- *Training on PEI procedures*: Although the PEI is expected to involve significant contribution above the State-level, State DOTs and lead agencies are encouraged to build and sustain solid PEI capabilities regarding hazards pertinent to each State following the successful example of Caltrans' Post Earthquake Investigation Team (PEQIT). PEI team members within the agency should become aware of the procedures, tools and protocols involved in all stages of a PEI plan, including reconnaissance missions, data collection, post-event network rehabilitation, disaster data processing, and long-term strengthening plans. Special training per PEI stage should be provided for teams specifically involved in that stage. Clear chains of command should be established and communicated between key personnel. Frequent exercises to assess and strengthen the capabilities of key personnel would assist the process.

- *Pilot projects*: Given that robust PEI frameworks are currently not the state-of practice within State DOTs or lead agencies, pilot PEI projects would greatly boost the learning curve for key personnel. By dramatizing the PEI steps under non-threatening conditions, procedures or team roles can be reviewed and perhaps modified to better reflect the resources, organizational structure and team expertise within the agency.

4.4.5 Inter-agency Coordination and Interdependencies

Business continuity in the aftermath of a disaster is very much dependent on the availability of timely information, the capacity to respond rapidly to this information, and the capacity to mobilize the necessary resources. The latter is, in turn, greatly affected by functional interdependencies between agencies and jurisdictions associated with the network. According to El Nakat (2015), several mechanisms may be established pre-disaster for the improvement of coordination between lead agencies, State DOTs, Federal and local governments, operators, and the private sector:

- Horizontal and vertical information networks that ensure the circulation of information before or during a disaster event. This demands a broad spectrum of expertise within all jurisdictions, as well as the development of good working relationships and coordination protocols, which can be formalized into memorandums of understanding or mutual aid arrangements. Systems can also be developed for cross-agency information sharing and data storing, such as the establishment of a point of contact at each agency, for the sourcing data, and the distribution of pre-established suggestions for data collection ex- ante and ex-post a disaster event.

- Agreements with the private sector with rates, roles, and contributions that will allow for the rapid mobilization and effective risk sharing, which will save time, cost, and resources.

- Discussion and review of recovery plans and long-term resilience strategies on a regular basis among lead agencies, State DOTs, highway operators, and local or Federal jurisdictions to ensure alignment of disaster management policies and facilitate consensus toward an effective post-disaster response.

4.4.6 User Participation in PEI Procedures

Agencies may benefit from investing in plans for the inclusion of users in the resilience-building process. It is essential to raise awareness to all users potentially affected by a disaster, with the primary goal being to create participants during emergency operations instead of victims. The users should develop a culture of mutual support and acquire a sense of “ownership” for the assets at stake. Where feasible, users may be trained to monitor and inspect transportation infrastructure and flag early warning signs or post-event damage in a dedicated domain.

It would also prove useful to establish a constant information flow between lead agencies, State DOTs, operators, and users, including plans for timely dissemination of disruption and travel information. The agency’s short-term recovery plans and long-term strengthening strategies could be publicly available at established points of reference (e.g., web-based public information platforms).

What is more, agencies may capture and assess user frustration in the aftermath of disasters as a quantifier of success for their current recovery practices. Post-disaster user survey can be a simple yet effective tool for receiving qualitative feedback on this metric. For this purpose, lead agencies and State DOTs may build upon and modify standardized user survey procedures employed during normal operating conditions. For instance, the National Road User’s Satisfaction Survey conducted in the United

Kingdom aims to obtain feedback across each of Highways England’s seven regions as part of the Government’s Roads Reform program.[25]

4.4.7 PEI Team Members

The PEI team structure may differ among departments based on the needs and strategies adopted by each agency. This study provides a typical list of key members and their corresponding contributions within the PEI Stage:

- **PEI Champion (PEIC):** A key person who ensures that team members are on track to complete the PEI procedures successfully and on time. The PEIC is responsible for communicating with team members and all associated stakeholders, identifying the PEI objectives in coordination with the involved stakeholders, translating these objectives to the PEI team members, and tracking the process of the PEI from the beginning to the end. The PEIC is also involved in milestone decisions regarding the prioritization of actions during the distinct PEI phases. The PEIC should be in close cooperation with the EMC of the PDI stage.

- **Reconnaissance Team Coordinator (RTC):** The RTC is responsible for overall coordination and communication during reconnaissance missions. The RTC assembles the field team, ensures availability of the necessary resources, and makes sure that data collection protocols are being followed. The RTC is also responsible for reporting results to the central interdisciplinary association.

- **Engineers (Structural, Geotechnical, Hydraulic etc.):** Engineers originating from the agency’s Structural Division or external engineering consultants in agreement with the State DOT to assist in PEI procedures. These are typically the same SMEs who coordinate specialty inspections on structural, geotechnical, hydrological, mechanical, and materials issues during the PDI stage. They form an integral part of the process, as they participate in the reconnaissance missions, the special engineering studies following field reconnaissance, the immediate repair plans and network strengthening strategies of the PEI stage.

- **Database Coordinator:** Responsible for the seamless operation of the central agency database (Database for Resilience). The Database Coordinator oversees the IT experts and data analysts and makes sure that data are provided in the most useful form to decision-makers. They are in close cooperation with the Emergency Data Coordinator of the PDI Stage, regarding the assessment of post-disaster damage data.

- **GIS and Information Technology (IT) experts/Data analysts:** This is the same task force involved in the PDI Stage. Data analysts and IT experts are necessary in the PEI action plan to process and analyze pre- and post-event data received at the agency’s database and ensure data quality.

- **Traffic Engineers:** This is the same task force involved in the PDI Stage for the assessment of traffic data, identification of lifelines, prioritization of inspection routes, and identification of optimum post-event detours. During the PEI stage, traffic engineers are responsible for processing post-event traffic data to inform metrics regarding the operational condition of the network and communicate the modified network conditions to the public amid reconstruction works.

- **Economists:** Responsible for assessing the cost-benefit analyses results and for advising the agency officials on appropriate investment strategies. Internal consultants or external consultants in agreement with the State DOT may be employed in this position to assist in PEI procedures.

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[25] https://www.transportfocus.org.uk/insight/national-road-users-satisfaction-survey/

- **Social and Environmental experts:** Responsible for assessing the social/environmental data assembled before and after a disaster, and for providing input to decision-makers regarding the social/environmental impact of selected repair and strengthening actions.
- **Federal representatives:** Officials belonging to the USDOT and other departments related to disaster preparedness and response may participate in the long-term strategic plans of the PEI stage, including representatives from the statistical agency, as well as from finance, economic, environmental, and social planning or other key departments.
- **Local representatives:** Responsible for providing local pre-and post-disaster data to the agency in accordance with the established information networks. Local representatives work together with the State DOT on the adopted course of action in the case of a local disaster.

Table 4-5: Connection of the "4.4. Long-term Resilience Building Strategies" with the Resilience Evaluation Tool. The adopted procedures increase the scale of the following measures.

Pillar	**Lens**	**Dimension**	**Measure**	**Reference to relevant Methodology Subsection**
Functionality	Robustness	Technical	*"Asset/System Condition"*	*4.4.3. Lifecycle Instrumentation and Monitoring*
	Robustness	Technical	*"Effective Maintenance"*	*4.4.3. Lifecycle Instrumentation and Monitoring*
	Robustness	Technical	*"Upgrade Plans"*	*4.4.2. Network Strengthening Plans [Prioritization Process]*
	Robustness	Socio-economic	*"Injuries and Life-Loss"*	*4.4.2. Network Strengthening Plans*
	Robustness	Socio-economic	*"Direct and Indirect Losses"*	*4.4.2. Network Strengthening Plans*
Adaptability and Operability	Security	Technical	*"Risk Assessment and Scenario Planning"*	*4.4.2. Network Strengthening Plans*
	Rapidity	Technical	*"Functional Recovery Time"*	*4.4.1. Collection of baseline and post-disaster data*
	Rapidity	Socio-economic	*"Users Readiness to Change"*	*4.4.6. User participation in PEI procedures*
	Rapidity	Socio-economic	*"Volunteering in Event Response Activities"*	*4.4.6. User participation in PEI procedures*
Database, and PDI and PEI Practices	Data Collection and Management	Organizational	*"Database Updating Procedures"*	*4.4.1. Collection of baseline and post-disaster data*
	Data Collection and Management	Organizational	*"Data Monitoring Frequency"*	*4.4.3. Lifecycle Instrumentation and Monitoring*
	Training	Organizational	*"Training Availability"*	*4.4.4. Interagency Engagement and Training*
	Training	Organizational	*"Staff Evaluation during Drills"*	*4.4.4. Interagency Engagement and Training*
Multi-Level Governance	Responsibility	Organizational	*"Organizational Structure"*	*4.4.5. Intra-agency Coordination and Interdependencies;* *4.4.7. PEI Team Members*
	Responsibility	Organizational	*"Intraorganizational Promotion of Resilience Culture"*	*4.4.5. Intra-agency Coordination and Interdependencies;* *4.4.6. User participation in PEI procedures*
	Networks	Organizational	*"Inter-agency Coordination and Cooperation"*	*4.4.4. Interagency Engagement and Training;* *4.4.7. PEI Team Members*

Pillar	Lens	Dimension	Measure	Reference to relevant Methodology Subsection
	Networks	Organizational	*“Interdependencies and Business Continuity Planning”*	*4.4.5. Intra-agency Coordination and Interdependencies*
	Leadership and Culture	Organizational	*“Engagement and Awareness of Staff”*	*4.4.4. Interagency Engagement and Training*
	Leadership and Culture	Organizational	*“Stakeholder Engagement Policies”*	*4.4.5. Intra-agency Coordination and Interdependencies;* *4.4.6. User participation in PEI procedures*
Adaptability and Operability	Mobility	Socio-economic	*“Loss of Productivity, Frustration”*	*4.4.6. User participation in PEI procedures*

Chapter 5 Data Collection Framework

5.1 Database for Resilience

The suggested “Database for Resilience” framework **supports the resilience-building process by identifying the entire range of data useful for the assessment of post-disaster network condition and the evaluation of long-term resilience-building plans**. Agencies could compile a comprehensive dataset of the life-long performance of individual assets and the network as a whole, including physical damage data and rehabilitation reports, but also condition, traffic, and financial data.

The framework involves 4 distinct phases for data collection (Figure 5-1):

- Asset classification and benchmarking: Inventory data and benchmark data (referring to the initial structural state of an asset).
- Normal operations: Asset condition data, cost and financial data, traffic data.
- Disaster event occurrence: Hazard data and physical damage data.
- Post-event performance and recovery metrics: Network functionality data, social data, loss data.

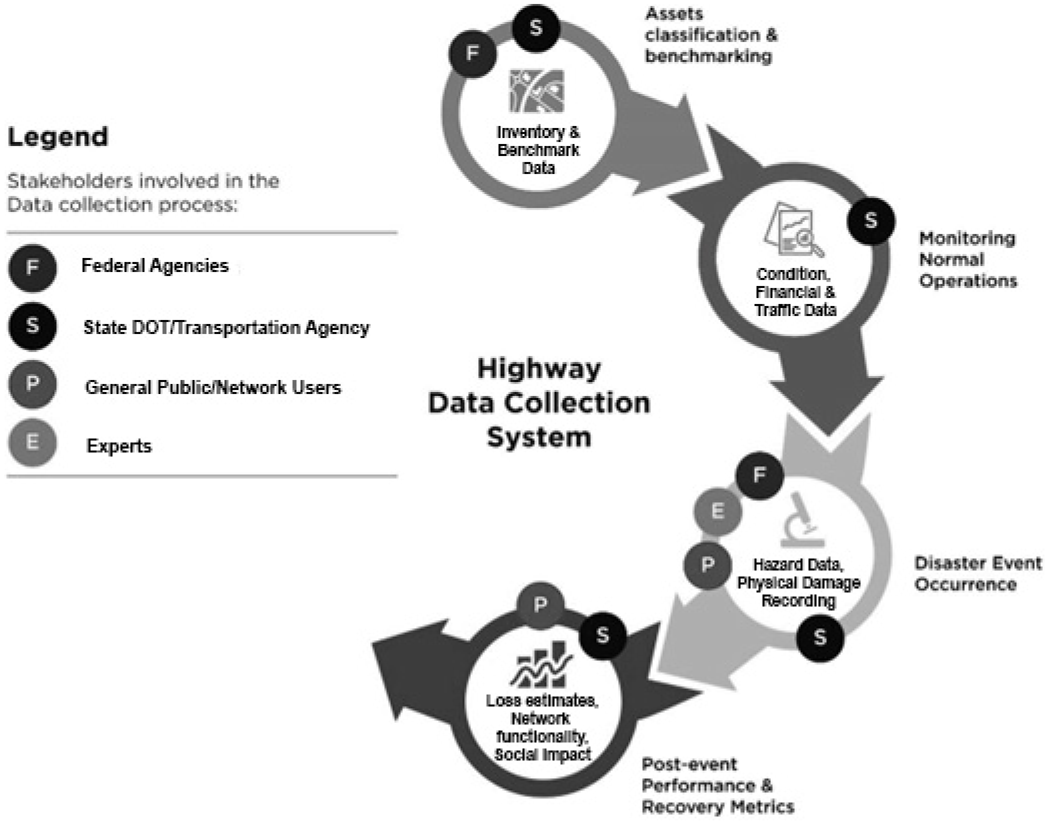

Figure 5-1: Data collection phases for the suggested Database for Resilience and stakeholders involved in the process (image by the authors)

The four major stakeholders involved in the data collection process, along with the data collection phases, are identified in Figure 5-1 and comprise State DOTs, Federal agencies, network users, and engineering experts.

The Database for Resilience involves both pre-event (baseline) and post-event network data related to the disaster impact assessment. Baseline data from phases A and B refer to any information available prior to the occurrence of a disaster, while post-event network data from phases C and D refer to the data collected in the aftermath of the disaster event (PDI and PEI Data). The data may be used collectively by lead agencies and State DOTs in assisting disaster management practices and in determining the best allocation of resources during post-event recovery planning.

Data collection procedures for inventory data, routine inspection data, traffic data, hazard data, and damage data have already been discussed in chapter 3. The main purpose of chapter 5 is to elaborate further on the remaining data categories (e.g., socio-economic data), and provide transportation agencies with a comprehensive catalog of data to be collected in the aftermath of a disaster, along with the most prevalent methods and tools employed for their collection.

The datasets fall under 11 main categories, largely based on Kadar (2009) and Maguire (2009):

- Inventory Data (e.g., asset ID, asset geo-location).
- Routine Inspection Data (e.g., asset condition ratings).
- Design and Construction Records (e.g., as-built drawings and photos).
- Traffic Data (e.g., Average Daily Traffic, Origin-Destination matrices, detour lengths).
- Hazard Data (e.g., USGS seismic hazard maps, FEMA Flood Maps).
- Disaster Damage Data (e.g., Structural/geotechnical damage of assets, Utilities damage).
- Post-Disaster Economic Loss Data (e.g., direct losses due to damaged assets or losses due to reduction in tolls revenue).
- Cost Data (e.g., maintenance costs, reconstruction costs).
- Network Functionality/Level of Service Data (e.g., functional recovery time, asset operational level, road capacity).
- Financial Data for macroeconomic analysis (e.g., fiscal budget, estimates of expenditure).
- Social Data (e.g., casualties, socio-demographic characteristics of network users, user frustration).

The first six categories have been outlined within the PDI methodology, while the remaining five pertain mostly to PEI procedures and are collected to inform indicators about long-term resilience. However, such categorization is not strict, in the sense that a category of PDI data may also be useful for PEI endeavors (e.g., hazard data, which are vital for pre-event planning strategies). It should be mentioned that a significant percentage of the data included in the first four categories is readily available for bridges and tunnel structures within the NBI and NTI databases.

5.1.1 Determination of Data Collection Level

Data collection strategy does not need to apply at the same level of detail for all asset-specific data. The data lists outlined in section 5.2 are extensive, and in many cases expensive equipment may be needed for their collection (e.g., use of SHM, non-destructive testing, or remote sensing techniques). Even though specific data sets are suggested, the amount of data collected for each set and the data accuracy should be tailored to address the criticality and risk levels of the asset of interest. For example, an SHM system for measuring deformations would not be needed for a bridge of low exposure to natural hazards, or low impact in the case of damage, but would be needed for an asset of high importance, such as a bay bridge connecting two cities on either side of the bay.

Based on the strategy developed by Bush et al. (2012) for bridge structures, the current study suggests the use of three data collection levels, based on the individual asset risk and criticality:

- **The core data collection level**, which corresponds to assets of low risk or low criticality. The information gathered at this level should be equivalent to that provided by the NBI and NTI databases for bridge and tunnel structures respectively.
- **The intermediate data collection level**, which corresponds to assets of increased risk and criticality, important for the network operations.
- **The advanced data collection level**, which corresponds to assets of high risk or high criticality, essential for the network operations.

Transportation agencies could perform risk and criticality assessments to identify the critical network assets for which an advanced data collection strategy (possibly accompanied with a monitoring system) should be implemented. Bush et al. (2012) includes an assessment procedure. Knowledge of the asset inventories, the pertinent natural hazard risks, and the network operation and asset replacement costs are needed to carry out the assessment. Following the assessment, a core, intermediate, or advanced data collection strategy can be assigned to each asset. The latter should be updated periodically; any changes to risk and/or criticality should entail adjustment of the data collection strategy.

5.2 Data Types and Collection Procedures

5.2.1 Asset Classification and Benchmarking

5.2.1.1 Inventory Data

Inventory data refers to systematic digital databases for all distinct asset typologies included in an agency’s portfolio (e.g., bridges, tunnels, culverts, retaining walls, and embankments). Digital databases will allow for the rapid query, comparison, and analysis of asset information, and ideally should be connected to a GIS environment.

Asset inventories compile information such as geo-location, typology, material, geometric characteristics, or other pertinent information that can help classification procedures. The FHWA has already produced unified nationwide databases for the Nation’s bridges (NBI) and tunnels (NTI). Lead agencies may consider compiling and maintaining in-house digital inventories for assets for which Federal databases do not exist to date (e.g., geo-structures). Any other information relevant to the asset (e.g., drawings, reports, construction records, and/or photos) may also be included in the digital inventory (Table 5-1).

Table 5-1: Additional inventory data: photos, designs, and construction records (Bush et al., 2012).

Data Items	Comment
Photographs	(No information)
Reports	Any report written regarding the asset
Construction reports/site records	Details of work carried out on the asset
Drawings	Drawing numbers, drawing names, drawing locations, drawing coverage description

5.2.1.2 Benchmark Data

Many of the existing deterioration models employed to assess an asset's lifecycle performance have no starting reference. Agencies should collect benchmark data at asset commissioning to assist the development of deterioration models.

Indicative benchmark data for bridge structures may include cover levels, chloride levels, concrete strength, reinforcement strength and critical element stresses, channel conditions for bridges that are built over waterways, or baseline topography (indicating ground slope and soil conditions) for geo-structures.

5.2.2 Monitoring Normal Operations

5.2.2.1 Asset Condition Data

Data relevant to the lifecycle performance of assets offer important base information for post-event evaluation. Agencies may develop an asset condition data list, pertinent to the assets of interest, based on their own needs and practices. Existing asset management systems could be modified to incorporate any additional information.

Table 5-2: Asset condition data (Bush et al., 2012).

Data Items	Comment
Condition ratings (severity and extent)	For assets and asset components
Scour evaluation ratings	For assets over waterways
Seismic performance ratings (where applicable)[26]	For all relevant assets
Collection methodology	Noted as collected by visual inspection, NDE or SHM
Maintenance Activities	Stored as planned work
Condition deterioration models	E.g., concrete deterioration models due to corrosion effects
Inspection program	Dates and outcome of asset routine inspections

5.2.2.2 Traffic Data

Traffic data are important for assessing the anticipated recovery time of a highway and the associated indirect losses (e.g., loss of connectivity, revenue loss, etc.), taking its toll on network's resilience. A list of essential traffic data that could be available and frequently updated within the "Database for Resilience" is presented in Table 5-3. The "Priority lifelines per significant hazard" item refers to the mapping of network routes that support survivability and emergency response efforts following an emergency event, provide transportation facilities that are critical to life support functions for an interim period following an emergency event, and support statewide economic recovery (CH2M Hill, 2012).

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[26] Using rating systems such as the one provided in the FHWA "Seismic Retrofitting Manual for Highway Bridges" (FHWA, 2006).

Table 5-3: Traffic network data.

Data Item	Comment
Traffic levels (i.e., Annual Average Daily Traffic)	For the economic assessment and risk management of the network – used in network level modelling
Current Network Capacity (based on no. of lanes)	Network performance assessment
Network Capacity after the extreme event (based on no. of operational lanes)	Network performance assessment
Origin-Destination Matrices under normal network operation	Input for Network-level modelling
Priority lifelines per significant hazard	Input for Network-level modelling
Weight-in-Motion Data	Used to understand vehicle configurations
Traffic composition (heavy vehicles percentage)	For the economic assessment and risk management of the network – used in network level modelling

5.2.2.3 Financial Data

Financial data facilitates the development of economic models and links the operational and post-disaster asset outcomes to strategic resilience goals. There can be five data categories in this field, including a) valuation data, b) maintenance costs, c) improvement/retrofitting costs, d) operations data, and e) data for macroeconomic analysis.

Maintenance costs, in this case, refer to design, procurement, construction, and construction management of maintenance construction activities, as well as maintenance operations. They should be stored as a function of time, since maintenance activities undertaken in the present may be inexpensive, yet if neglected, they could escalate to a more significant issue (Bush et al., 2012).

Improvement/retrofitting costs correspond to all retrofitting actions, including design, procurement, construction, and construction management. Operations data provide basic input for undertaking economic cost-benefit analysis, such as by assessing the benefits gained from prioritizing the repair of an asset following an extreme event to restore traffic as soon as possible and reinstate toll revenues.

Table 5-4: Financial data: Valuation.

Data Item	Comment
Asset replacement costs	As this is detailed in the valuation
Annual depreciation	A function of remaining-life model
Depreciated replacement costs	Linked to remaining life and condition models

Table 5-5: Financial data: Maintenance costs.

Data Item	Comment
Initial estimates	(No information)
Planning estimates	(No information)
Construction costs	(No information)
Inspections costs	Equivalent annual cost per asset

Table 5-6: Financial data: Improvement/retrofitting costs.

Data Item	Comment
Initial estimates/Planning estimates	(No information)
Construction costs	(No information)

Table 5-7: Financial data: Operations.

Data Item	Comment
Monthly toll income	(No information)
Travel-time costs	Annual cost of time spent on transport within the network. Different travel time unit costs (dollars per hour) should be assigned to different types of travelers and travel conditions, based on the network's characteristics.
Vehicle-operating costs	Annual costs of vehicle usage (fuel, maintenance etc.) Strongly dependent on vehicle type and travel-time costs.
Accident costs	Annual cost of accidents occurring within the network

Table 5-8: Financial data for macroeconomic analysis.

Data Item	Comment
Fiscal budget	(No information)
Estimates of expenditure (CAPEX, Operational Expenses)	(No information)
Projections on economic growth	(No information)

5.2.3 Data Collection During/Following the Disaster Event

Data collection and storage during the PDI and PEI stages are sometimes hindered due to misinterpreted data needs, the inadequacy of storage systems, the misalignment of collection procedures, or the deviation from data format protocols. Such issues are discussed in chapters 3 and 4.

This section focuses on the detailed description of hazard and damage data that should be collected in the aftermath of a disaster event, presenting lists of data items and state-of-the-practice methods and tools for their collection. Data are classified based on asset and hazard type, including only hazards that may pose a threat to the performance of the asset under consideration.

5.2.3.1 Hazard Data

Typically, information involving hazard data is provided by Federal platforms, such as the USGS ShakeMap or the National Weather Dashboard by USGS.[27]

Table 5-9: Hazard data: Earthquake.

Data Item	Method/Device
Acceleration data	• Local acceleration network, USGS ShakeMaps of similar platforms

Table 5-10: Hazard data: Floods (flash floods, riverine floods, storm surges, hurricane surges, flood-induced scouring).

Data Item	Method/Device
Rainfall intensity and duration	• Network SHM software • Federal centers • NOAA National Hurricane Center and Hurricane Forecast Improvement Program • NOAA/ National Weather Service Storm Data (https://www.spc.noaa.gov/climo/online/) • National Centers for Environmental Information Storm Events database (https://www.ncdc.noaa.gov/stormevents/) • National Weather Dashboard (USGS)

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[27] https://dashboard.waterdata.usgs.gov/app/nwd/?aoi=default

Data Item	Method/Device
Discharge/Velocity of flowing water	- Stream Gaging Stations (flow sensors etc.)[28]
Inundation zone	- Visual Observation - Remote Sensing Imagery - Flood Delineation Tools
Flood depth	- National Weather Dashboard (USGS) - Local stream gages (manometer, float sensor gage, staff gage, water-stage recorder etc.) - Lidar Scans at Inundated Areas.

Table 5-11: Hazard data: Tsunami (Wave characteristics).

Data Item	Method/Device
Inundation and runup height	- Visual Observation - Remote Sensing Imagery
Indicate location and type of water body — open coast, bay, harbor, estuary.	- Visual Observation
Note direction from which wave came.	- Visual Observation - Questionnaire
Note nature of tsunami waves. Fast rising and falling tides? Breaking waves? Other?	- Visual Observation - Questionnaire
Did the water recede before first tsunami wave arrived?	- Visual Observation - Questionnaire

5.2.3.2 Damage Data

The following tables show structural, geotechnical, or hydraulic data that can be collected for each asset category, along with the most prevalent collection methods based on the state-of-practice or state-of-the-art. The lists aim to support consistent damage identification procedures during the PDI and PEI stages. The lists were assembled with the aid of several GEER and StEER reconnaissance reports, assisted by asset-specific or hazard-specific damage assessment suggestions, which are cited accordingly in the following sub-sections. The StEER reconnaissance reports were retrieved from https://www.steer.network/. The GEER reports may be found at http://www.geerassociation.org/reconnaissance-reports.

Bridges and Culverts:

Ground-induced hazards (Earthquake; Liquefaction; Earthquake – induced landslides)

Refer to the following publications for further information regarding the input of Table 5-12 and Table 5-13:

- Data collection and monitoring strategies for asset management of New Zealand road bridges: Research report RR 475 (Bush et al., 2012)
- Post-Earthquake Bridge Inspection Manual (Oklahoma Dept. of Transportation, 2016)
- First Responder Bridge Assessment Guide (FRBAG): Structure Maintenance and Investigations (SM&I) – (Caltrans, n.d.)

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[28] Gaging stations are often unavailable at bridge sites. Proper interpolation methods including additional sources or drain between the gaged location and bridge site are then implemented.

- Visual inspection and capacity assessment of earthquake damaged reinforced concrete bridge elements (No. CA08-0284) – (Veletzos et al., 2008)
- Manual for GEER Reconnaissance Teams, v.4. GEER (GEER, n.d.)
- Geotechnical Engineering Circular 5, Evaluation of Soil and Rock Properties (FHWA, 2002)
- The EERI's Learning from Earthquakes (LFE) "Post-Earthquake Investigation Field Guide" **(**http://www.learningfromearthquakes.org/activities/reconnaissance)

Table 5-12: Structural data for bridges and culverts after ground-induced hazard events.

Structural Data	Method/Device
Deck/Pier deflections/displacements	• Strain Gauges • Inclinometers • Photogrammetry (e.g., via UAS Inspection and 3-D image generation using "Structure-from-Motion" methodology) • Fiber Optics • LiDAR/Laser Scanning
Deck tilt/misalignment	• Visual Inspection • Inclinometers • Tiltmeters • LiDAR/Laser Scanning • UAS Inspection and Photogrammetry
Cracking/spalling (deck, piers, abutments)	• Visual Inspection • UAS Inspection and Photogrammetry • LiDAR/Laser Scanning • NDT (ultra-sonic testing, sounding with a hammer, rebar scanner etc) and Accelerometers (vibration-based methods)
Bearings' condition: displacement or misalignment, sheared anchor bolts, spalled or fractured concrete on pedestals or beams	• Visual Inspection • UAS Inspection and Photogrammetry • Inclinometers • Tiltmeters
Joints: expansion joint misalignment, displacement, unseating or broken seats support, loss of support for girders	• Visual Inspection • Photogrammetry
Buckling of steel elements/reinforcement	• Visual Inspection • NDT Testing
Sheared bolts or cracked and broken welds in steel connections	• Visual Inspection
Damage in secondary systems (utilities, parapets, railings, approaches)	• Visual Inspection

Table 5-13: Geotechnical data for bridges and culverts after ground-induced hazard events (e.g., permanent ground deformation or surface rupture).

Geotechnical Data	Method/Device
Geotechnical site characterization (soil properties, shear wave velocity logs, position of ground water table)	• Boreholes • Geophysical Methods (MASW or SASW) • Penetration Tests (e.g., DCPT)
Surface manifestation of liquefaction and lateral spreading	• Visual Inspection • Remote Sensing (satellites or drones)
Foundation/abutment deformations (lateral displacement, settlement, tilt)	• Strain Gauges at the deck • Visual inspection • Inclinometers • Tiltmeters • LiDAR/Laser Scanning • Photogrammetry • Sonar Scans
Abutment/embankment slope distress or movement	• Remote Sensing (Satellites or UASs and Photogrammetry) • Hand-held/Pre-Installed Inclinometers • Laser scanning
The structure intersects with surface manifestation of the causative fault	• Visual Inspection • Aerial Imagery (UASs)

Flood-induced scouring (flash floods, riverine floods, storm surge, hurricane surge)

Readers may refer to the following publications for further information regarding the input of Table 5-14 to Table 5-16:

- Evaluating Scour at Bridges. Publication No. FHWA-HIF-12-003 (FHWA, 2012)
- Structural health monitoring for performance assessment of bridges under flooding and seismic actions (Prendergast et al., 2018)
- First Responder Bridge Assessment Guide (FRBAG): Structure Maintenance and Investigations (SM&I) – (Caltrans, n.d.)
- Post-extreme event damage assessment and response for highway bridges (Alipour, 2016)

Table 5-14: Hydraulic data for bridges and culverts under flood-induced scouring.

Hydraulic Data	Method/Device
Geometry of the scour hole	Portable or fixed scour measuring devices: • Tethered Buried Switches • Ground Penetrating Radars • Fibre Bragg Water Swellable Polymers • Sounding Rods • Sonars • Vibration-Based Sensors (buried or driven rods) • Time Domain Reflectometers
Channel erosion (threatening bridge supports)	• Underwater Cameras/Inspections • Fixed/Portable/Unmanned Sonar Surveys
Soil Erodibility (optional)	• Submerged Jet-type Devices • Flume Tests
Streambed elevation data	• Sonar Surveys

Hydraulic Data	Method/Device
Bathymetric and topographic data	- Sonar Surveys - LiDAR/Laser Scanning
Debris existence/accumulation	- Visual Inspection

Table 5-15: Geotechnical data for bridges and culverts under flood-induced scouring.

Geotechnical Data	Method/Device
Soil properties (grain size distribution, plasticity, density, strength, and hydraulic conductivity)	- Laboratory Tests on Soil Samples - FHWA Ex-situ Scour Testing Device (ESTD) and In-situ Scour Testing Device (Lab-ISTD)[29]

Table 5-16: Structural data for bridges and culverts under flood-induced scouring.

Structural Data	Method/Device
Abutment or superstructure overtopping	- Visual Inspection
Pier/Abutment rotational movement or settlement	- Strain Gauges at the deck - Inclinometers - Tiltmeters - Photogrammetry - Fiber optics - LiDAR/Laser Scanning
Discontinuities, structural cracking, or spalling	- Visual Inspection - Photogrammetry - Accelerometers (Vibration-based Methods) - NDT (Magnetic Particle Testing, Dye Penetrant Testing, Ultra-Sonic Testing, Sounding with a Hammer, or Rebar Scanner) - LiDAR/Laser Scanning
Excessive movement of bridge seats	- Visual Inspection

Tsunamis:

Readers may refer to the following publications, for further information regarding Table 5-17 through Table 5-19:

- StEER: Structural Extreme Event Reconnaissance network: Palu earthquake and tsunami, Sulawesi, Indonesia Field Assessment Team 1 (FAT-1) Early Access Reconnaissance Report (EARR) (Kijewski-Correa and Robertson, 2018)

- The EERI's Learning from Earthquakes (LFE) "Post-Earthquake Investigation Field Guide" – section 15: https://www.eeri.org/wp-content/uploads/Field_Guide_Section_15.pdf

Table 5-17: Hydraulic data for bridges and culverts in a tsunami event.

Hydraulic Data	Method/Device
Bathymetry data (for submarine landslide or seabed offsets evidence)	- Sonar Scans, LiDAR Scans

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[29] https://highways.dot.gov/research/laboratories/hydraulics-research-laboratory/hydraulics-laboratory-zones

Table 5-18: Structural data for bridges and culverts under tsunami hazard.

Structural Data	Method/Device
Superstructure overtopping	• Visual Inspection
Discontinuities, structural cracking, or spalling	• Visual Inspection • Photogrammetry • NDT • LiDAR/Laser Scanning
Excessive movement of bridge seats	• Visual Inspection

Table 5-19: Geotechnical data for bridges and culverts in a tsunami event.

Geotechnical Data	Method/Device
Abutment/foundation deformations	• Visual Inspection • Inclinometers • Tiltmeters • Photogrammetry • Sonar scans
Soil properties at damaged structures	• Laboratory Tests on Soil Samples • Boreholes
Ground level characteristics (steep slopes, slope stability failures)	• Visual Observation

Tunnels:

Readers may refer to the following publications for further information regarding Table 5-20 through Table 5-21:

- Manual for GEER Reconnaissance Teams, v.4. GEER (GEER, n.d.)
- Geotechnical Engineering Circular 5, Evaluation of Soil and Rock Properties (FHWA, 2002)
- The FHWA "Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual" (FHWA, 2015)

Ground-induced hazards (Earthquake; Liquefaction; Earthquake – induced landslides)

Table 5-20: Structural data for tunnels after ground-induced hazard events.

Structural Data	Method/Device
Lining deformations	• Strain Gauges • Visual Inspection • Photogrammetry • Fiber Optics • Vibration-based Methods (Accelerometers)
Lining cracking/spalling	• Visual Inspection • Photogrammetry • NDT (Ground Penetrating Radar, Ultra-Sonic Testing, Sounding with a hammer, Rebar Scanner etc)
Movements at joints, offsets due to displacement across a fault	• Visual Inspection • Photogrammetry

Table 5-21: Geotechnical data for tunnels after ground-induced hazard events.

Geotechnical Data	Method/Device
Geotechnical site characterization (soil properties, position of ground water table)	• Boreholes • Geophysical Methods (MASW or SASW) • Penetration Tests (e.g., DCPT)
Surface manifestation of liquefaction and lateral spreading	• Visual Inspection • Remote Sensing (satellites or drones)
Evidence of tunnel intersection with the causative fault	• Existing Geotechnical Studies
Cracks, slides, or slope failures in embankments near the tunnel portals	• Visual Inspection • Photogrammetry • Hand-held/Fixed Inclinometers
Tilt in walls adjacent to the tunnel portals	• Visual Inspection • Inclinometers • Tiltmeter • LIDAR/Laser Scanning • UAS Inspection • Photogrammetry
Slope movements	• Remote Sensing (3-D image generated using "Structure-from-Motion" from a drone) • Fixed Instrumentation (inclinometers)
Rock falls and loose rock	• Visual Inspection, UAS Inspection

Hydraulic hazards

Impact from hydraulic hazards on tunnel structures refer to flooding due to water entering at the portals from heavy rainfall, overflowing rivers, or tsunami waves.

Table 5-22: Geotechnical data for tunnels in hydraulic hazard events.

Geotechnical Data	Method/Device
Geotechnical site characterization (Soil properties, position of ground water table)	• Laboratory Tests on Soil Samples • Boreholes
Deformation/instability checks of walls and slopes around the tunnel due to the saturation of embankments and slopes around the tunnel with water.	• Strain Gauges • Visual Inspection • Inclinometers • Tiltmeters • Photogrammetry
Pore pressures (embankments may become unstable due saturation with water)	• Piezometers

Table 5-23: Damage to Electromechanical tunnel equipment due to hydraulic hazard events.

Electromechanical Equipment	Method/Device
Electrical systems can be ruined by floodwaters, especially if they are exposed to saltwater in the process	• Visual Inspection

***Retaining Walls*:**

Ground-induced hazards (Earthquake; Liquefaction; Earthquake – induced landslides)

Table 5-24: Geotechnical data for retaining walls after ground-induced hazard events.

Geotechnical Data	Method/Device
Geotechnical site characterization (soil properties, position of ground water table)	• Boreholes • Geophysical Methods (MASW or SASW) • Penetration Tests (e.g., DCPT)
Surface manifestation of liquefaction and lateral spreading	• Visual Inspection • Remote Sensing (satellites or drones)
Slope movements	• Remote Sensing (3-D image generated using "Structure-from-Motion" from a drone) • Fixed Instrumentation (inclinometers)

Table 5-25: Structural data for retaining walls after ground-induced hazard events.

Structural Data	Method/Device
Deformations (horizontal displacements, tilting)	• Strain Gauges • Photogrammetry • Hand-held Inclinometers • Fiber Optics
Concrete wall cracking/spalling	• Visual Inspection • Photogrammetry • NDT (Ground Penetrating Radar, Ultra-sonic Testing, Sounding with a hammer, Rebar Scanner etc)

Hydraulic hazards (Flooding; Scour; Coastal erosion; Surge; Tsunami)

Table 5-26: Geotechnical data for retaining walls under hydraulic hazard events.

Geotechnical Data	Method/Device
Geotechnical site characterization (soil properties, position of ground water table)	• Boreholes • Penetration Tests (e.g., CPT) • Laboratory Tests
Pore pressures in retained soil	• Piezometers

Table 5-27: Structural data for retaining walls in hydraulic hazard events.

Structural Data	Method/Device
Concrete wall cracking/spalling	• Visual Inspection • Photogrammetry • NDT (Ground Penetrating Radar; Ultra-sonic testing, Sounding with a hammer, Rebar Scanner etc)
Deformations (horizontal displacements, tilting due to backfill settlement/displacement)	• Strain Gauges • Visual Inspection • Photogrammetry • Hand-held Inclinometers • Fiber Optics

***Highway embankments*:**

Ground-induced hazards (Earthquake; Liquefaction; Earthquake – induced landslides)

Table 5-28: Geotechnical data for embankments after ground-induced hazard events.

Geotechnical Data	Method/Device
Subsurface profile (soil, groundwater, shear wave velocity profile),	• Site Investigations (Boreholes, CPT, SASW, MASW)
Geometry/properties of predefined shear zone within the soil	• Site Investigations (CPT, SASW, MASW)
Deformations (subsidence, horizontal displacements)	• Photogrammetry • Fixed Instrumentation (e.g., Inclinometers)
Surface manifestation of liquefaction and lateral spreading (e.g., sand boils)	• Visual Inspection • UAS Inspection
Landslide occurrence: latitude, longitude, area, and volume involved	• Aerial Imagery (UASs and Structure from Motion techniques)

Hydraulic hazards (Rainfall-induced slides; Erosion due to storm surge or tsunami)

Table 5-29: Geotechnical data for embankments in hydraulic hazard events.

Geotechnical Data	Method/Device
Subsurface profile (soil, groundwater, shear wave velocity profile)	• Site Investigations (Boreholes, CPT)
Pore pressures (embankments may become unstable due saturation with water)	• Piezometers
Landslide occurrence: latitude, longitude, area, and volume involved	• Aerial Imagery
Deformations (subsidence, horizontal displacements)	• Photogrammetry • Fixed Instrumentation (e.g., Inclinometers)

5.2.4 Post-Event Performance and Recovery Metrics

5.2.4.1 Direct and Indirect Loss Data

Calculation of direct losses involves mapping the hazard-induced physical damage on the highway infrastructure. The latter is translated into a damage ratio and multiplied by the estimated net present value of the asset reconstruction cost to produce the direct loss value.

Indirect disaster losses arise from disruptions to the flow of goods and services, and typically include both the decline in revenues and the impact on the well-being of network users. The data item listed herein refers to the first component by measuring the post-disaster reduction in toll revenues and the loss due to potential claims. This metric needs consistent monitoring of post-event toll revenues and comparison with pre-event values. The social impact of the disaster on network users is quantified under the category of “Social Data.”

Table 5-30: Direct and Indirect Loss Data.

Data Item	Comment
Direct losses due to damaged assets	Based on physical damage ratio data and asset reconstruction costs
Indirect losses due to reduction in tolls revenue	Based on post-event tolls revenue monitoring

5.2.4.2 Network Functionality Data

Network functionality data illustrate the post-event level of service offered by the network. These metrics aim to assist lead agencies in improving post-event rehabilitation plans and making informed decisions about network needs. Post-disaster information is highly time-dependent; therefore, network functionality data should be collected at multiple fractions of time after the event to determine the trends of network recovery (Horney et al., 2018). Three types of metrics are identified below. These metrics reflect post-event recovery actions, post-event network performance, and the level of business interruption to network suppliers.

Table 5-31: Network functionality and emergency response data.

Data Item	Comment
Functional recovery time	For the evaluation of post-event recovery strategies.
Full recovery time	For the evaluation of post-event recovery strategies.
Post-event average travel speed	For the evaluation of post-event network performance and prioritization of retrofit strategies.
Post-event highway length open to traffic	For the evaluation of post-event network performance and prioritization of retrofit strategies.
Post-event travel time to destination	For the evaluation of post-event network performance and prioritization of retrofit strategies.
Supply chain efficiency	For the evaluation of business interruption levels.

Based on the definitions provided in a recent NIST and FEMA report (Kersting et al., 2021), functional recovery refers to safe network usage and restoration of network components and services to support a significant measure of pre-event functionality. Full recovery refers to restoration to the pre-event safety and functionality of the network (Kersting et al., 2021). Lead agencies may derive the metrics by carefully monitoring the reconstruction works and post-event network operations. Furthermore, agencies could establish and apply standardized documentation procedures so that consistent comparisons with historical data or future disaster events are made.

Surveys to the suppliers that use the network on a day-to-day basis may be useful for measuring post-event supply chain efficiency, such as by measuring the fluctuations of appropriate Key Performance Indicators (e.g., “On Time Delivery”) (García-Arca et al., 2018).

5.2.4.3 Social Impact

Data on injuries and life-loss are the primary metric used by agencies and institutions to account for the social impact of a disaster event (Deloitte Access Economics, 2016). Lead agencies may actively include users in the resilience-building process by also establishing post-event user surveys directed at representative groups of affected population. The latter can assist in monitoring the effectiveness of network recovery efforts and increase the available information to agencies, thereby enabling reconstruction efforts to be more tailored to user needs.

Agencies may also collect background user information by contacting local government offices in the affected areas to gather pre-disaster socio-demographic data. This information offers an additional dimension in the network’s resilience assessment and assists in identifying urgent areas for intervention (e.g., when a densely populated area of low-income residents faces the threat of being cut off from public hospital access due to a failed bridge).

Table 5-32: Social data.

Data Item	Comment
Injuries and life-Loss	Data from FEMA
Socio-demographic characteristics of network users	Local Government Offices
Post-event user satisfaction/frustration	User Surveys – Rating of the network/network links and their commute post-event (Excellent, Good, Fair, Poor)

Chapter 6 Demonstration Test Case

6.1 Resilience Assessment Framework

The RET mentioned in chapter 2 aims to ensure a comprehensive, systematic, and consistent lifecycle measurement of resilience in any highway structure. It consists of more than 120 quantifiable measures across four pillars (Functionality; Adaptability and Operability; PDI and PEI Practices; Multi-Level Governance and Database), several lenses (Rapidity, Robustness, Data Collection and Management, etc.) and the resilience dimensions (Technical, Organizational, and Socio-economic).

The general philosophy of the tool lies in the quantification of several measures on a scale from 1 (very low resilience) to 4 (very high resilience). First, weights are assigned on a measure-level ("Measure Weights"), dimension-level ("Dimension Weights" – W_{Dim}), lens-level ("Lens Weights" – W_{Lens}), and lastly pillar-level ("Pillar Weights" – W_{Pil}). The sum of the weights within a certain level should be 1 or 100 percent. Each measure then receives a score between 1 and 4. The overall resilience score is calculated from the bottom up (i.e., from the more specific level to the more general). First, the measure scores are assigned, multiplied by the respective measure weight, and then summed up to yield the "Dimension Score." The Dimension Scores within a lens are multiplied by the Dimension Weights and summed up to yield the "Lens Score." The Lens Scores within a pillar are then multiplied by the Lens Weights and summed up to yield the "Pillar Score." Finally, the Pillar Scores are multiplied by their Pillar Weights and summed up to yield the "Resilience Score."

6.2 Custom Resilience Evaluation Tool Versions

Custom applications of the RET are also supported (e.g., by removing or assigning a weight of 0 to indicators, lenses, or pillars that cannot be easily assessed). One such example is described in the next section, where the resilience assessment of an example highway network is performed on the basis of only 16 measures, outlined in Figure 6-1, along with their respective dimensions, lenses, and pillars. The measures are also summarized in Table 6-1 to Table 6-6 with an explicatory "Measurement Scale", which helps the user more consistently and objectively rate each measure. The weights have been selected based on the relevance and significance of each measure to the post-event recovery of the highway portfolio. As previously discussed, the sum of all measure weights of a given dimension (e.g., technical) must equal 1. As a result, the impact of a unit change in the score of a single measure (to the overall resilience score) equals (1/N) x (W_{Dim}) x (W_{Lens} x (W_{Pil}) where "N" is the number of measures per dimension (assuming equal measure weights within the same dimension).

As such, dimensions that are described by a single measure (i.e., N=1), will by default contribute more to the overall resilience score than others, introducing a systematic weighting bias in the calculations (favoring single-entry dimensions). The latter may be counterbalanced by appropriately adjusting the Dimension Weighting Parameter (W_{Dim}). For example, lower W_{Dim} may be assigned to the organizational dimension of the robustness lens than to technical dimension within the same lens.

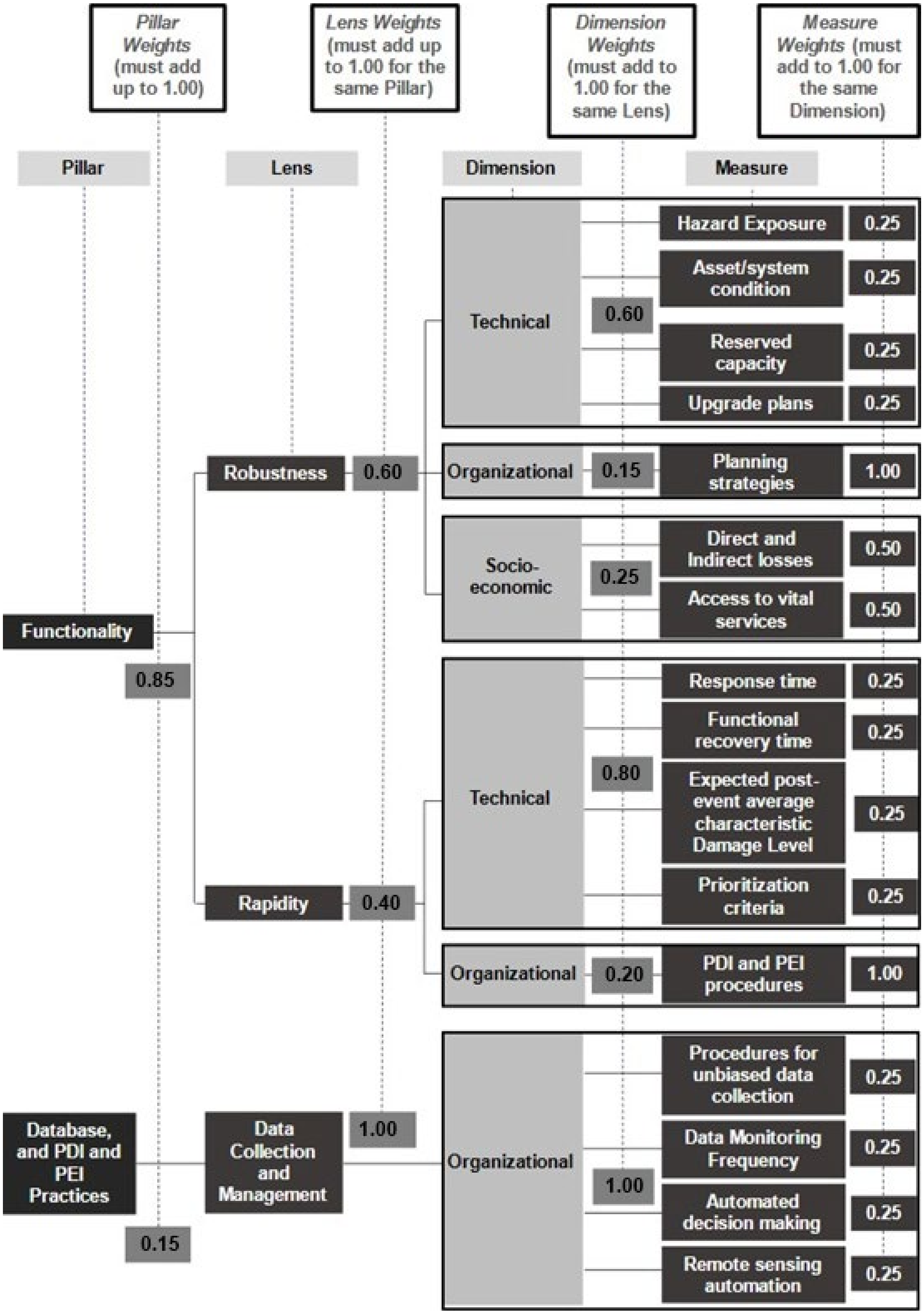

Figure 6-1: Measures considered organized in pillars, lenses, and dimensions, with the respective weights (pillar, lens, dimension, and measure weights) (image by the authors)

Table 6-1: The 16-measure version of the Resilience Evaluation Tool: Functionality/Robustness/Technical (Pillar/Lens/Dimension).

Measure	Measurement Scale
Hazard Exposure	**4**-Very low exposure to specific hazards
	3- Low exposure to specific hazards
	2- Moderate exposure to specific hazards
	1- Severe exposure to specific hazards
Asset/system condition	**4**- New, like new, recently retrofitted
	3- Slightly deteriorated, needs light retrofit
	2- Average condition, needs significant retrofit
	1- Poor condition, needs upgrades/reconstruction
Reserved capacity	**4-** Asset have at least 75 percent reserved capacity above normal demand capacity
	3- Asset have at least 50 percent reserved capacity above normal demand capacity
	2- Asset have some reserved capacity above normal demand capacity
	1- Asset have no reserved capacity above normal demand capacity
Upgrade plans	**4**- Upgrade plans are updated and implemented to address resilience
	3- Upgrade plans address resilience, but are not implemented
	2- Upgrade plans do not address resilience
	1- No upgrade plans

Table 6-2: The 16-measure version of the Resilience Evaluation Tool: Functionality/Robustness/Organizational (Pillar/Lens/Dimension).

Measure	Measurement Scale
Planning strategies	**4**- Plans are well developed, tested, followed, and regularly reviewed and updated
	3- Plans exist but are inconsistent, not tested, and have some gaps
	2- Ad hoc plans undertaken or plans being drafted
	1- No plans

Table 6-3: The 16-measure version of the Resilience Evaluation Tool: Functionality/Robustness/Socio-economic (Pillar/Lens/Dimension).

Measure	Measurement Scale
Direct and Indirect losses	Annual cost of required repair/renewal due to impacts of extreme events is:
	4- Less than 5 percent of the asset value
	3- Less than 10 percent of the asset value
	2- Less than 20 percent of the asset value
	1- In excess of 20 percent of the asset value
Access to vital services	**4**- Access to vital service is not interrupted
	3- Access to vital services is interrupted for few hours
	2- Access to vital services is interrupted for 24-48 hours
	1- Access to vital services is interrupted for longer than 48 hours

Table 6-4: The 16-measure version of the Resilience Evaluation Tool: Functionality/Rapidity/Technical (Pillar/Lens/Dimension).

Measure	Measurement Scale
Response time	**4**- Immediately after the event
	3- Less than an hour after the event
	2- Less than two hours after the event
	1- Greater than two hours after the event
Functional recovery time	Scale depends on the importance of transportation asset. For a critical transportation asset:
	4- Less than 8 Hours
	3- Less than 24 hours
	2- Less than 72 Hours
	1- More than 72 Hours
Expected post-event average characteristic Damage Level	**4**- CDL1 – No Damage
	3- CDL2 – Minor/Slight Damage
	2- CDL3 – Moderate Damage
	1- CDL4 – Extensive Damage or Collapse
Prioritization criteria	**4**- Criteria are well established, tested, followed, and regularly reviewed and updated
	3- Criteria exist, but have gaps
	2- Ad hoc criteria or criteria being drafted
	1- No criteria

Table 6-5: The 16-measure version of the Resilience Evaluation Tool: Functionality/Rapidity/Organizational (Pillar/Lens/Dimension).

Measure	Measurement Scale
PDI and PEI procedures	**4**- Procedures are well developed, documented, tested, and regularly reviewed and updated
	3- Procedures exist, but are not well developed, documented, tested, or regularly reviewed and updated
	2- Procedures are being developed and drafted
	1- No Procedures

Table 6-6: The 16-measure version of the Resilience Evaluation Tool: Database, and PDI and PEI Practices/Data Collection and Management/Organizational (Pillar/Lens/Dimension).

Measure	Measurement Scale
Procedures for unbiased data collection	**4**- Procedures are well developed, followed, and regularly reviewed and updated
	3- Procedures exist, but are inconsistent, have some gaps, or are not reviewed and updated regularly
	2- Ad hoc procedures
	1- No procedures
Data Monitoring Frequency	**4**- Regular and frequent monitoring
	3- Regular, but infrequent monitoring
	2- Irregular monitoring
	1- No monitoring
Automated decision making	Connection to decision making
	4- Database is strategically and automatically connected to action plan recommendations to support decision making
	3- Tools and approaches are being developed to link the database to decision making
	2- Tools and approaches for linking the database to decision making are being discussed
	1- No connection between database and decision support
Remote sensing automation	**4**- Defined and tested methodology exist for the use of remote sensing and mechanisms for information gathering (crowd sourced) to feed an established information platform for the critical asset
	3- Defined, but untested methodology exists for the use of remote sensing and mechanisms for information gathering (crowd sourced) to feed an established information platform for the critical asset
	2- Methodology under development with a clear testing plan
	1- No knowledge or development of a methodology or platform

6.3 Step-by-step Deployment of the Resilience Evaluation Tool for a Highway Transportation Structure Portfolio Exposed to Seismic Hazard

6.3.1 Example Problem Statement

For this demonstration case, the hazard considered is earthquake and the asset portfolio comprises 13 highway transportation structures in New York State. The bridges have different structural types, number of spans, age of construction (spanning from 1936 to 2018), and locations, thereby creating a diverse portfolio of assets in terms of hazard exposure and structural vulnerability. The key properties of the assets considered are provided in Table 6-7. Their locations are illustrated in Figure 6-2.

Table 6-7: Key properties of the selected bridges in New York State.

NBI Item 8 – Struct. Number (ID)	Lat.	Long.	Year of Construction	Skew angle	NBI Item 43- "Structure Type, Main"	Number of spans	Length of max. span	Tot. length of transportation structure
(-)	**(°)**	**(°)**	**(-)**	**(°)**	(**A** *XX*)	**(-)**	**(m)**	**(m)**
1006110	41.043462	73.490402	1936	0	**1** *04*	3	15.5	41.5
1009810	42.100781	75.525488	2003	30	**1** *05*	1	22.6	23.8
1017670	42.191132	74.261121	2018	40	**3** *02*	2	61.3	121.9
1018309	40.424956	73.202058	1968	24	**3** *02*	3	22.8	41.5
1024009	44.555919	74.531362	2018	25	**3** *02*	4	71	258.2

NBI Item 8 – Struct. Number (ID)	Lat.	Long.	Year of Construction	Skew angle	NBI Item 43- "Structure Type, Main"	Number of spans	Length of max. span	Tot. length of transportation structure
1024360	42.511726	76.263621	1992	30	**1** *05*	1	19.5	20.7
1055359	40.451288	73.443962	2002	4	**2** *05*	2	50.3	100.3
2231450	40.350965	73.544424	2017	0	**4** *02*	3	59.7	151.2
2231471	40.361236	73.535876	2017	0	**3** *02*	17	71.3	808.6
3338190	44.563134	74.234614	1969	0	**3** *02*	2	21.3	44.2
3337850	44.532147	74.332608	1947	0	**3** *02*	3	18.3	44.5
1037700	44.571282	74.502067	1956	0	**3** *03*	5	49.7	187.5
3337820	44.421397	74.082931	1957	0	**1** *05*	1	10.9	11.6

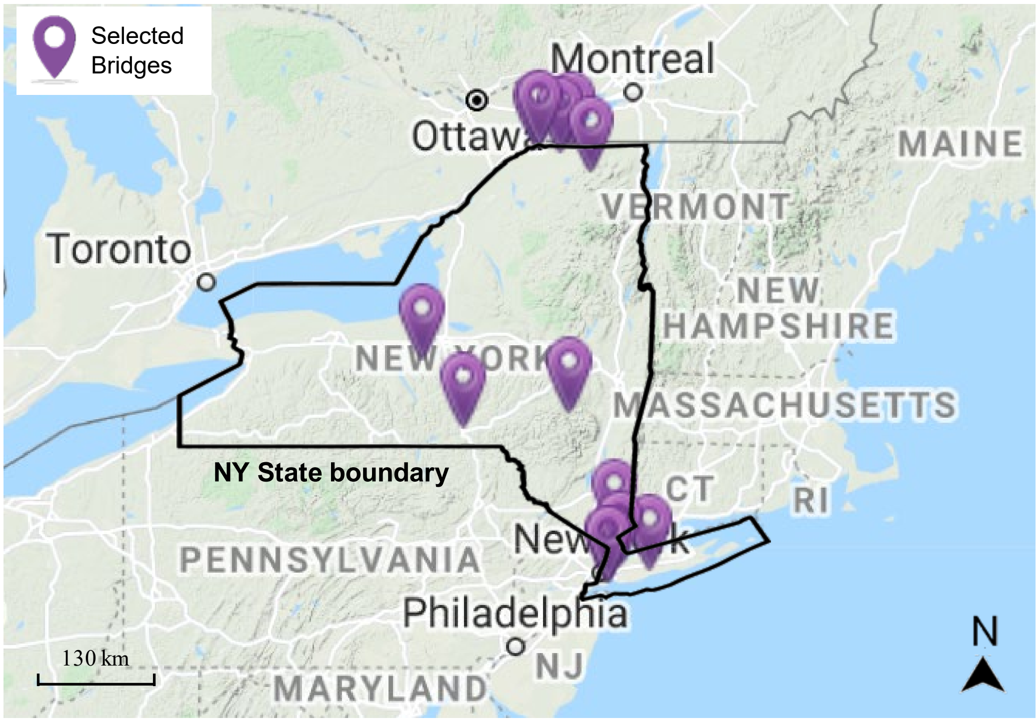

Figure 6-2: Overview of the highway transportation structure portfolio considered in the Resilience Evaluation Tool Demonstration Case Study (image by the authors)

6.3.2 Resilience Strengthening Alternatives

The objective of this section is to evaluate the impact of two alternative investments on the seismic resilience of the network when compared to a baseline scenario (corresponding to the “do nothing” strategy), namely structural retrofit of selected transportation structures, and installation and operation of a network of accelerometers and displacement sensors.

- **The first alternative** consists of upgrading the structural systems of transportation structures that highly contribute to the total damage of the highway portfolio due to their high exposure to the seismic hazard and/or due to ageing and degradation effects that jeopardize their seismic capacity. One or more transportation structures are retrofitted in the superstructure (e.g., seat extenders, shear keys, restrainer cables, etc.) and substructure (e.g., steel jackets in reinforced concrete piers, bent cap retrofit, foundation retrofit etc.) in accordance with the latest seismic design codes. A robust estimation of the cost of retrofit (CAPEX) has not been attempted. For the purpose of this example, the cost of retrofit is approximated as a fixed percentage (equal to 30 percent) of the construction cost of a new (identical) transportation structure (Buckle et al., 2006).

- **The second alternative** focuses on the technological upscale and monitoring enhancement of the highway portfolio. Specifically, a network of accelerometers and Linear Variable Differential Transducers is installed both in between transportation structures along the highway network (on the roadsides), and on selected transportation structures. The deployed monitoring network provides acceleration data in the free field, in a distance from the transportation structures where the ground shaking intensity is independent of any soil-structure interaction effects, as well as acceleration and displacement data on the monitored structures. With proper manipulation, the sensing data can be converted into damage data (e.g., maximum drift of the pier, or information about pier yield based on the acceleration response). The monitoring network is assumed to be supplemented by an automated digital data collection system (wireless, wired, or hybrid), and a GIS-enabled platform to gather and geo-reference the sensing data. To calculate the total investment cost of this alternative, it is assumed that each transportation structure needs on average two accelerometers (average market price $1,000 each) to be installed on it or in the vicinity of it for ground shaking information. The automated data collection system and the GIS-enabled platform for rapid damage assessment has an installation cost (hardware and IT infrastructure, average market price) of $150,000 and applies to the entire network. As a result, the CAPEX for this alternative is $150,000 plus $2,000 per monitored structure.

Each alternative has a beneficial role reflected through different resilience measures. However, the increase in the score is a function of the thoroughness of the intervention and the associated level of investment. The summary of both alternatives is outlined in Table 6-8, along with their investment costs. Details about the implementation of the two suggested strategies on the portfolio are presented under “Step 3” of the following section.

Table 6-8: Resilience Strengthening Alternatives and associated investment costs.

Resilience Strengthening Alternatives	**General Description**	**CAPEX** (per transportation structure)
Structural retrofit of transportation structures	One or more transportation structures are retrofitted in the superstructure and substructure in accordance with the latest seismic design codes.	**30 percent of New Construction Cost** (FHWA, 2006)
Installation and operation of a network of accelerometers and displacement sensors	A sensing network of accelerometers and displacement sensors is installed and operated on one or more transportation structures. Post-event and lifecycle structural performance are measured. Warnings are sent to the operator in case of damage induced by an extreme event.	**$2,000/structure** + **$150,000** for integration platform

6.3.3 Deployment of Resilience Evaluation Tool to evaluate investment alternatives

An initial resilience assessment is performed to measure the baseline resilience score for the assumed seismic scenario. Then, the resilience strengthening alternatives are identified and evaluated based on their potential to enhance resilience. The two alternatives are chosen so as to correspond to different levels of investment.

Step 1: Seismic Assessment of the Baseline Scenario – “Do nothing” Option

The assessment is performed in general accordance with the seismic loss estimation methodology of the HAZUS-MH framework, and is composed of three steps:

1. **The regional seismic hazard** is based on probabilistic seismic hazard maps. Different return periods or probabilities of exceedance correspond to different spatially distributed hazard intensities, expressed as PGA, PGV, SA [1.0 sec], etc. For illustration purposes (although not compatible with current design and retrofit practice), a higher version of the New York State earthquake hazard level is assumed, corresponding to a 4,975-year return period. There are several reasons for using this scenario for the demonstration:

    - The selected 4,975-year return period is in better accordance with the risk-targeted seismic design concept (Luco et al., 2015), which would indicate a dominant earthquake scenario greater than the design earthquake in the eastern United States resulting in 1 percent in 50 years likelihood of asset collapse.

    - To achieve “beyond-code” seismic resilience, disaster planning should transcend the “life safety” objectives of current code provisions. The network should be prepared to withstand earthquake events that overly exceed the customary design levels. Hence, when assessing its earthquake resilience, the network's response should be checked against “beyond-code” hazard levels rather than code-compatible spectra, which correspond to the design capacities of its assets and therefore are not expected to be causing any significant damage to the network.

    - The HAZUS-MH methodology tends to overestimate the “true” capacity of the example bridges, as it neglects damage modes caused by high-frequency motions (which are common for New York State bridges), as well as structural deterioration effects due to ageing. As such, if a moderate return period were chosen (e.g., the AASHTO 1000-year design earthquake), most of the analyzed bridges would have been tagged as green, rendering the need of any investment unjustifiable.

2. **The direct physical damage** induced by the ground shaking on each transportation structure is evaluated based on readily available fragility functions. Each fragility function has been developed for distinct structure classes, namely different geometry configurations, material properties (concrete or steel), structure designs (conventional or seismic), etc. For a given seismic hazard intensity (i.e., return period in Step 1), a probability distribution is provided by the fragility function for five damage states, and the distribution is translated to a unique CDL for each asset. The CDL is defined as the damage level at which the probability of exceedance it is higher than 20 percent at a given seismic hazard intensity, defined here by SA [1.0 sec]. The selected CDLs are “No Damage,” “Minor/Slight Damage,” “Moderate Damage,” “Extensive Damage,” and “Collapse.”

3. **The indirect damage** is qualitatively assessed based on the restoration times (days) and loss of asset functionality (percentage). To this end, the assigned CDL of each asset is correlated with the restoration time needed to bring the asset back to its pre-event condition and the asset’s functionality in certain intervals after the considered event, based on the HAZUS-MH framework. For instance, a moderately damaged structure (CDL “Moderate Damage”) takes 10 days on average to fully restore and has an expected functionality recovery equal to 30 percent one day after the earthquake event, 95 percent after a week, and 100 percent after a month.

Step 2: Resilience Score of the Baseline Scenario

The score of each measure is based on a series of assumptions and needs to follow the suggested measurement scale. Two measures (out of a total of 16) can be fully quantifiable based on the output of Step 1. More specifically, the measures “Direct and Indirect losses” and “Expected post-event average characteristic Damage Level” in this test case received a score based on the rationale presented below:

Direct and Indirect losses	**Score:**
Functionality > Robustness >> SE	**3** (out of 4)

For the seismic event under consideration, three transportation assets (asset ID: 3338190, asset ID: 3337580, asset ID: 1037700) experience extensive structural damage and three (asset ID: 1006110, asset ID: 1018309, asset ID: 1024009) have minor to slight damage. This is translated to specific Loss Estimates (LE): Direct losses due to physical damage and rehabilitation/replacement needs and Indirect losses expressed in Restoration Time (days) and Loss of Asset Functionality (percentage). Then, a "Direct and Indirect Loss" indicator, which is calculated based on the ratio of LE over the Total Value (TV) (equal to 4 for LE/TV < 5 percent, equal to 3 for LE/TV between 5 percent and 10 percent, equal to 2 for LE/TV between 10 percent and 20 percent, and equal to 1 for LE/TV > 20 percent) is deployed to assign a score to the measure. Here, LE is estimated at $8,115,080.00, and the TV of the bridge portfolio is equal to $ 127,042,000.00 (NBI data); therefore, LE/TV is 6.38 percent (between 5 percent and 10 percent) and the score is 3.

Expected post-event average characteristic Damage Level	**Score:**
Functionality > Rapidity >> Technical	**2** (out of 4)

Post-event CDLs are also calculated by the Earthquake Risk Assessment Toolkit for each asset separately. The three assets with extensive structural damage are assigned a CDL equal to 40 percent, as per the toolkit's methodology, while the three assets with minor to slight damage have a CDL of 3 percent. As this point, engineering judgement is needed to translate the asset-level CDLs to a network-level CDL. Using the arithmetic mean of CDLs for all the assets results in a network-level CDL of 9.92 percent,[30] which is higher than CDL2 (3 percent) and lower than CDL3 (15 percent). Conservatively, CDL3 is selected, and the measure receives a score of 2.

The scoring process for measures that do not solely rely on the outcome of the toolkit is indicatively described below for two measures.

Hazard Exposure	**Score:**
Functionality > Robustness >> Technical	**1** (out of 4)

The seismic exposure of the network (i.e., of the expected consequences) is judged as high given the intensity of the seismic scenario analyzed and the importance of network. Therefore, a score equal to 1 is selected.

Asset/Network Condition	**Score:**
Functionality > Robustness >> Technical	**3** (out of 4)

As can be observed from the transportation structure data of Table 6-7, six structures, namely 46 percent of the highway portfolio, are now over 50 years old, hence some ageing and/or structural degradation effects may have deteriorated their condition. The NBI "Recoding and Coding Guide for the Structure Inventory and Appraisal of the Nation's Transportation structures" (FHWA, 1995) provides a condition indicator (NBI inventory, items 58 through 62) for several transportation structure components on a scale from 0 (failure) to 9 (excellent condition), which is useful when scoring this measure. According to the NBI indicator, the older structures have a condition indicator spanning from 4.0 (asset ID: 1006110) to 8.5 for the superstructure and substructure. With an average of 6.3 (out of 9), their condition is satisfactory to

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[30] (7 × 0 percent + 3 × 3 percent + 3 × 40 percent)/13 = 9.92

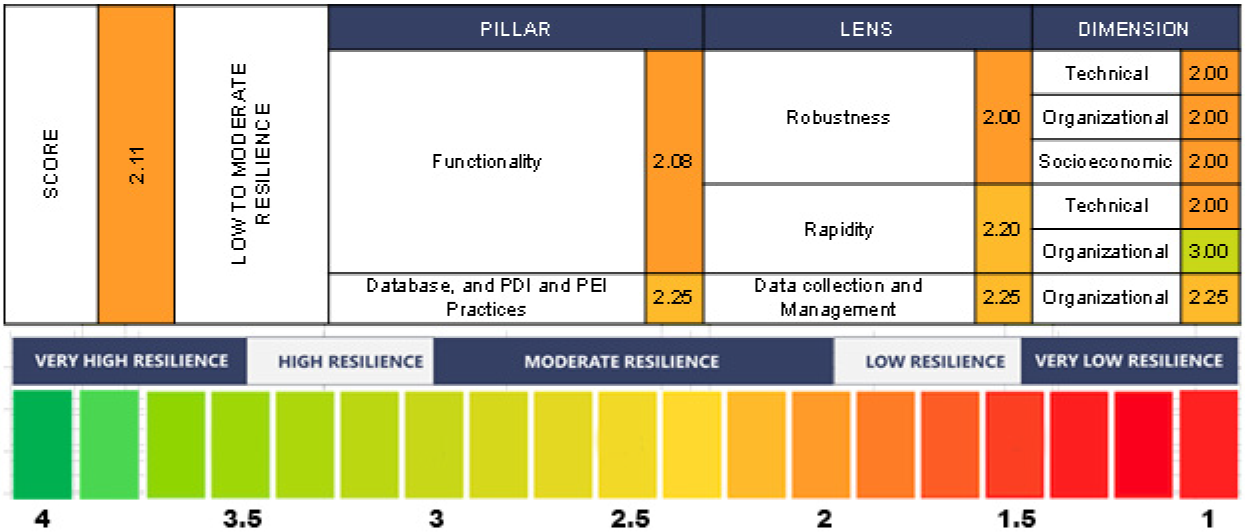
good. It may be concluded that a highway asset portfolio with 46 percent transportation structures older than 50 years (but at satisfactory to good condition), and 54 percent newer transportation structures (most of which were constructed after the 2000s) receives a score of 3.

For the rest of the measures, engineering judgement and consultation with experts was deployed to assign a reasonable score (portrayed in Table 6-9). To derive the Total Resilience Score, all Dimension Scores within a lens are multiplied by the Dimension Weights and summed up to yield the Lens Score. The Lens Scores are then multiplied by the Lens Weights to produce the Pillar Score. Finally, the Total Resilience Score is the weighted average of the Pillar Scores. In this demonstration test case Baseline Resilience Score = 2.11 (out of 4).

The intermediate results per level considered (dimension, lens, and pillar) can be found in Figure 6-3.

Table 6-9: Resilience Assessment scores of each measure for the baseline scenario.

Pillar/Lens/Dimension	**Measure**	**Measure Weight**	**Measure Score** (out of 4.00)	**Dimension Total** (out of 4.00)
Functionality/Robustness/Technical	Hazard Exposure	0.25	1	**2**
	Asset/system condition	0.25	3	**2**
	Reserved capacity	0.25	3	**2**
	Upgrade plans	0.25	1	**2**
Functionality/Robustness/Organizational	Planning strategies	1	2	**2**
Functionality/Robustness/Socio-economic	Direct and Indirect losses	0.5	3	**2**
	Access to vital services	0.5	1	**2**
Functionality/Rapidity/Technical	Response time	0.25	2	**2**
	Functional recovery time	0.25	1	**2**
	Expected post-event average characteristic Damage Level	0.25	2	**2**
	Prioritization criteria	0.25	3	**2**
Functionality/Rapidity/Organizational	PDI and PEI procedures	1	3	**3**
Database, and PDI and PEI Practices/Data Collection and Management/Organizational	Procedures for unbiased data collection	0.25	3	**2.25**
	Data Monitoring Frequency	0.25	3	**2.25**
	Automated decision making	0.25	2	**2.25**
	Remote sensing automation	0.25	1	**2.25**



SCORE	2.11	LOW TO MODERATE RESILIENCE	PILLAR		LENS		DIMENSION	
			Functionality	2.08	Robustness	2.00	Technical	2.00
							Organizational	2.00
							Socioeconomic	2.00
					Rapidity	2.20	Technical	2.00
							Organizational	3.00
			Database, and PDI and PEI Practices	2.25	Data collection and Management	2.25	Organizational	2.25

Figure 6-3: Resilience Assessment Score for the baseline scenario (with no risk reduction and resilience enhancement measures). Two pillars are considered (image by the authors)

The implementation of the two alternatives is planned as follows:

- **Resilience Strengthening Alternative 1**: Structural retrofit of transportation structures.

The prioritization of structural retrofit can be performed in multiple ways and is usually informed by the damage distribution under the seismic event of each case. Intuitively, assets that contribute the most to direct and indirect losses should be retrofitted first. However, advanced retrofit prioritization or optimization tools should be utilized, to provide robust and data-driven decisions. In this case, the three transportation assets (asset ID: 3338190, asset ID: 3337580, asset ID: 1037700) that experience extensive structural damage are planned to be retrofitted.

The Total Investment Cost of this alternative is a percentage of the New Construction Cost of each transportation structure. This cost, referred to as the “Total Replacement Cost” is equal to the cost for building a new transportation structure at the same location today to serve the exact same needs as the ones of the existing structure. The replacement is designed following the latest Seismic Design Codes. An estimate of this cost can be retrieved from the NBI inventory (item 94 – Transportation structure Improvement Cost). The structural retrofit cost for each of the three transportation assets with extensive damage in the 4,975-year seismic event, are:

- New Construction Cost of asset ID: 3338190 is $739,000. Consequently, Retrofit Cost of asset ID: 3338190 is 30 percent x $739,000 = approximately $220,000.
- New Construction Cost of asset ID: 3337580 is $953,000. Consequently, Retrofit Cost of asset ID: 3337580 is 30 percent x $953,000 = approximately $280,000.
- New Construction Cost of asset ID: 1037700 is $3,903,000. Consequently, Retrofit Cost of asset ID: 1037700 is 30 percent x $3,903,000 = approximately $1,100,000.

This results in a total investment of $1.6 million.

Step 3a: A Resilience Score is calculated for Alternative 1.

The beneficial role of this alternative is quantified by means of the following measures:

- **Reserved Capacity:** the retrofitted assets have over 75 percent reserved capacity above normal demand; therefore, the overall highway portfolio has increased capacity. The updated score of this measure is 4 (3 in the baseline scenario).

- **Direct and Indirect losses**: the retrofitted assets should be tested with the direct and indirect earthquake damage assessment methodology for the same seismic event. Given their increased capacity and ductility, they are expected to experience a lower level of physical damage, thereby reducing the portfolio losses. The updated score of this measure is 4 (3 in the baseline scenario).

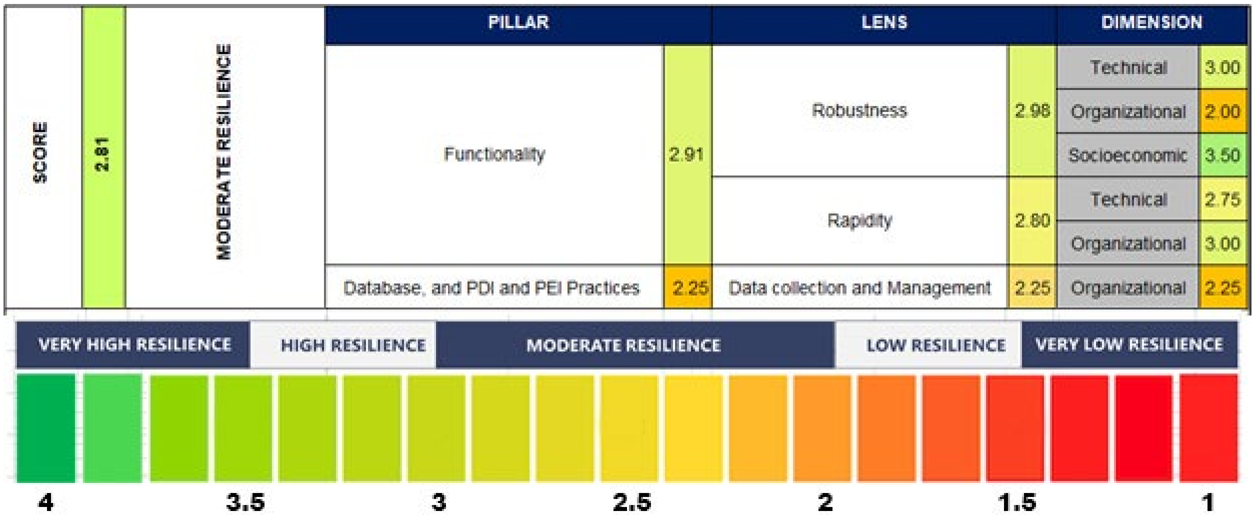
- **Access to vital services**: the retrofitted assets will remain operable, while asset ID: 3338190 is expected to disrupt the access to vital services of the network for longer than 48 hours. The upgraded network is more resilient but cannot receive a perfect score. The updated score is 3 (1 in the baseline scenario).

- **Functional recovery time**: The retrofit is directly reflected in the reduction of rehabilitation time for each damaged asset and has therefore reduced the functional recovery time of the network. As one asset is still extensively damaged, the updated score is 3 (1 in the baseline scenario).

- **Expected post-event average CDL**: As only one asset in the portfolio is expected to be at CDL4 – Extensive Damage or Collapse, as per the pre-retrofit results of the direct and indirect earthquake damage assessment, the updated score is 3.0 (2 in the baseline scenario).

The updated Resilience Score for the Alternative 1 is summarized in Figure 6-4.

The Resilience Score for Alternative 1 is 2.81 (out of 4).



			PILLAR		LENS		DIMENSION	
SCORE	2.81	MODERATE RESILIENCE	Functionality	2.91	Robustness	2.98	Technical	3.00
							Organizational	2.00
							Socioeconomic	3.50
					Rapidity	2.80	Technical	2.75
							Organizational	3.00
			Database, and PDI and PEI Practices	2.25	Data collection and Management	2.25	Organizational	2.25

Figure 6-4: Resilience Assessment Score for the case of the first remedial alternative (image by the authors)

Step 3b: A Resilience Score is calculated for Alternative 2.

In accordance with Table 6-8 the total investment cost of this alternative is estimated at $2,000 per asset, plus $150,000 for the whole transportation network. Instrumentation of six out of 13 network bridges is considered, corresponding to a total investment cost of $162,000.

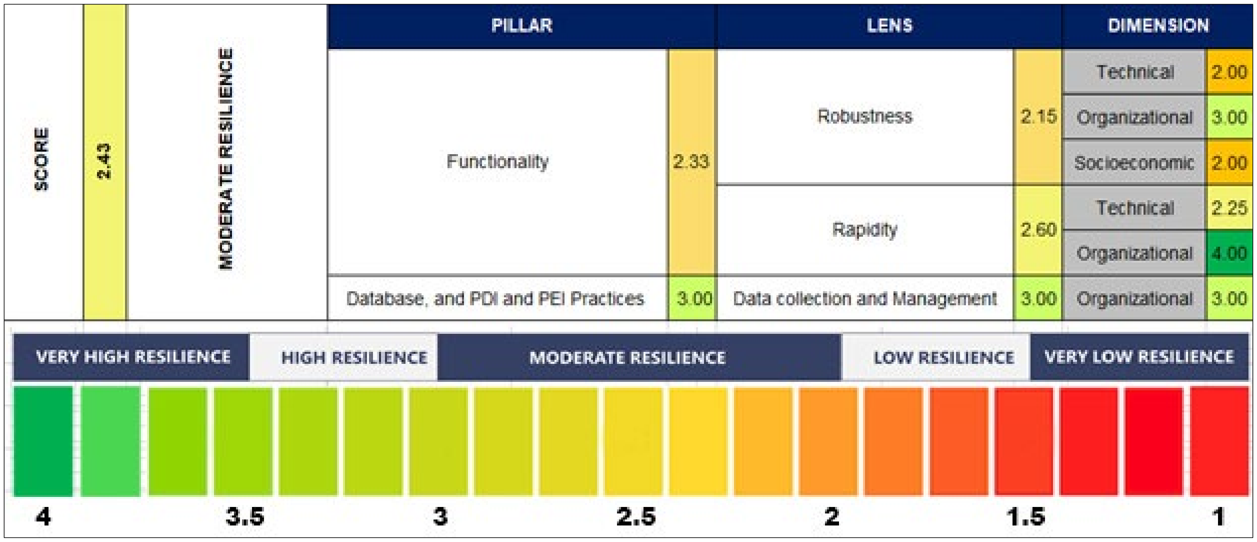
The beneficial role of this alternative is captured and quantified in the following measures:

- **Planning strategies**: Enhancing preparedness in the pre-event planning phase and developing risk assessment frameworks is facilitated by gathering and processing higher resolution data with advanced sensing networks. Therefore, the score of this measure is 3.0 (2 in the baseline scenario), as the investment budget could not cover all assets. Should the sensing strategy have included all the assets, then a score of 4 would have been assigned.

- **Response time**: The data from the sensing network will travel and be processed centrally, yielding a rapid condition assessment for each asset that is monitored at the network. Such information is valuable and drastically reduces the response time. The updated score is 3 (2 in the baseline scenario), as the immediate response teams are expected to be at the damaged assets less than an hour after the event.
- **PDI and PEI procedures**: As presented in chapter 4, high tech, frequent or continuous, and distributed data collection frameworks, largely enabled by sensing networks, are at the cornerstone of enhanced PDI and PEI procedures. The incorporation of sensors in four assets not only provides valuable data for the lifecycle assessment of their structural performance but can also be utilized to send emergency alerts in the case of the seismic event and rapidly inform about their structural condition and/or need for emergency response. The updated score is 4 (3 in the baseline scenario).
- **Data monitoring frequency**: Regular and frequent monitoring will be in place after the installation of the sensing systems in the most critical assets of the highway portfolio. The updated score is 4 (4 in the baseline scenario).
- **Automated decision-making**: This measure is expected to increase by one unit, as databases with lifecycle assessment, hazard, and damage data will be updated with the new sensing systems. The updated score is 3 (2 in the baseline scenario).
- **Remote sensing automation**: This measure is targeted to critical assets. As more and higher resolution data will be made available in an automated manner with wired or wireless sensing infrastructure, the updated score is 2 (1 in the baseline scenario).

The updated Resilience Score for the Alternative 2 is summarized in Figure 6-5.

The Resilience Score for Alternative 2 is 2.43 (out of 4).



SCORE			PILLAR		LENS		DIMENSION	
SCORE	2.43	MODERATE RESILIENCE	Functionality	2.33	Robustness	2.15	Technical	2.00
							Organizational	3.00
							Socioeconomic	2.00
					Rapidity	2.60	Technical	2.25
							Organizational	4.00
			Database, and PDI and PEI Practices	3.00	Data collection and Management	3.00	Organizational	3.00

Figure 6-5: Resilience Assessment Score for the case of the second remedial alternative (image by the authors)

Step 4: Select Investment Strategy

Alternative 1 has increased the Resilience Score by 35 percent, while Alternative 2 has increased it by 15 percent. However, the second alternative corresponds to a significantly lower investment cost (equal to 12 percent of the first one). The ultimate responsibility lies with the decision maker who would be weighing not only the enhanced resilience but also other parameters, including availability of funds, social factors, and policy planning. In order to support such decisions, the presented tool could be used in conjunction with other available platforms that are able to run cost-benefit analyses (e.g., NIST's Economic Decision Guide Software Tool[31]).

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[31] https://www.nist.gov/services-resources/software/edge-economic-decision-guide-software-online-tool

Chapter 7 References

Alaska Dept. of Transportation. (2014). *Incident Field Operations Guide*.

Alipour, A. (2016). *Post-extreme event damage assessment and response for highway bridges (No. Project 20-05, Topic 46-11)*.

Alzughaibi, A. A., Ibrahim, A. M., Eltawil, A. M., Na, Y., and El-Tawil, S. (2019). Post-disaster structural health monitoring system using personal mobile-phones. *2019 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*, 1–4.

Barrow, R. S. ., Anthony, R. W. ., Beasley, K. J. ., and Verhulst, S. M. . (2018). *Guidelines for failure investigation*.

Blanchard, B. A., Bohuslav, T. R., Schneider, C., Anderson, S., Schexnayder, C. J., DeWitt, S. D., Raymond, G., and Sheffield, R. (2009). Best Practices in Accelerated Construction Techniques. *NCHRP Project 20-68A*, *Scan 07-02*.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. https://doi.org/10.1193/1.1623497

Bush, S., Omenzetter, P., Henning, T., and McCarten, P. (2012). Data collection and monitoring strategies for asset management of New Zealand road bridges: Research report RR 475. *New Zealand Transport Agency*.

Caltrans. (n.d.). *First Responder Bridge Assessment Guide (FRBAG): Structure Maintenance and Investigations (SM&I)*.

Casarotti, C., and Pinho, R. (2007). An adaptive capacity spectrum method for assessment of bridges subjected to earthquake action. *Bulletin of Earthquake Engineering*, *5*(3). https://doi.org/10.1007/s10518-007-9031-8

CH2M Hill. (2012). *Oregon Seismic Lifelines Identification Project: Seismic Lifelines Evaluation, Vulnerability Synthesis, and Identification*.

Chen, Y.-W., and Tzeng, G.-H. (1999). A fuzzy multi-objective model for reconstructing the post-quake road-network by genetic algorithm. *International Journal of Fuzzy Systems*, *1*(2).

Davis, C. A. (2019a). Infrastructure System Resilience: Functionality and Operability. *2nd International Conference on Natural Hazards and Infrastructure*.

Davis, C. A. (2019b). A proposed performance based seismic design process for lifeline systems. *Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Proceedings of the 7th International Conference on Earthquake Geotechnical Engineering, 2019*, *Paper No.*, 1986–1993.

Deloitte Access Economics (2016). The economic cost of the social impact of natural disasters. Australian Business Roundtable for Disaster Resilience and Safer Communities.

El-Anwar, O., Ye, J., and Orabi, W. (2016). Efficient Optimization of Post-Disaster Reconstruction of Transportation Networks. *Journal of Computing in Civil Engineering*, *30*(3). https://doi.org/10.1061/(asce)cp.1943-5487.0000503

El Nakat, Z. S. (2015). Disaster risk management in the transport sector: a review of concepts and international case studies. No. 98202. *The World Bank*.

Executive Order 14008. (2021). https://www.govinfo.gov/content/pkg/FR-2021-02-01/pdf/2021-02177.pdf

FEMA. (2020). *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time*.

Fengler, W., Ihsan, A., and Kaiser, K. (2012). Managing post-disaster reconstruction finance: International experience in public financial management. In *From the Ground Up: Perspectives on Post-Tsunami and Post-Conflict Aceh*. https://doi.org/10.1355/9789814345200-010

FHWA. (1995). Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, *Federal Highway Administration Report FHWA-PD-96-001, December 1995* .

FHWA. (2002). Geotechnical Engineering Circular 5, Evaluation of Soil and Rock Properties*, Federal Highway Administration Publication No. FHWA-IF-02-034, April 2002*.

FHWA. (2006). Seismic Retrofitting Manual for Highway Structures*:* Part 1 -Bridges*, Federal Highway Administration Publication No. FHWA-HRT-06-032, January 2006*.

FHWA. (2012). Hydraulic Engineering Circular No. 18, *Evaluating Scour at Bridges, Fifth Edition, Federal Highway Administration Publication No. FHWA-HIF-12-003, April 2012*.

FHWA. (2015). Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual. *Federal Highway Administration Publication No. FHWA-HIF-15-005,. July 2015*.

FHWA. (2017). Resilience and Transportation Planning, *Federal Highway Administration Publication No. FHWA-HEP-17-028*, January 2017.

FHWA. (2018). *FHWA Major Project Delivery Process*. https://www.fhwa.dot.gov/majorprojects/defined.cfm

FHWA.(2022), Promoting Resilient Operations for Transformative, Efficient, and Cost- Saving Transportation (PROTECT) Formula Program Implementation Guidance, Federal Highway Administration Information, July 2022, https://www.fhwa.dot.gov/environment/sustainability/resilience/policy_and_guidance/protect_formula.pdf.

FHWA. (2022). FHWA Strategic Plan FY 2022-2026, *Federal Highway Administration Publication No. FHWA-PL-23-010*, May 2023.

Filosa, G., Plovnick, A., Stahl, L., Miller, R., and Pickrell, D. H. (2017). Vulnerability Assessment and Adaptation Framework (Report No. FHWA-HEP-18-020). *Federal Highway Administration. Office of Planning, Environment, and Realty. United States*.

Freeman, S. A. (1998). Development and use of capacity spectrum method. In *Proceedings of the 6th US NCEE Conference on Earthquake Engineering/EERI* (Issue Paper 269).

García-Arca, J., Prado-Prado, J. C., and Fernández-González, A. J. (2018). Integrating KPIs for improving efficiency in road transport. *International Journal of Physical Distribution and Logistics Management*.

GEER. (n.d.). Manual for GEER Reconnaissance Teams, v.4. GEER. *GEER (Geotechnical Extreme Events Reconnaissance)*.

Goswami, S., Chakraborty, S., Ghosh, S., Chakrabarti, A., and Chakraborty, B. (2018). A review on application of data mining techniques to combat natural disasters. *Ain Shams Engineering Journal*, *9*(3), 365–378. https://doi.org/https://doi.org/10.1016/j.asej.2016.01.012

Horney, J. A., Dwyer, C., Chirra, B., McCarthy, K., Shafer, J., and Smith, G. (2018). Measuring Successful Disaster Recovery. *International Journal of Mass Emergencies and Disasters*.

Jalinoos, F., Agrawal, A. K., Brooks, C. N., Amjadian, M., Banach, D. M., Boren, E. J., and Ahlborn, T. M. (2019). Post-hazard engineering assessment of highway structures using remote sensing technologies (No. FHWA-HIF-20-004). *U.S. Federal Highway Administration. Office of Infrastructure Research and Development.*

Kadar, P. (2009). Guide to asset management part 6: inventory. *Sydney: Austroads*.

Karlaftis, M. G., Kepaptsoglou, K. L., and Lambropoulos, S. (2007). Fund Allocation for Transportation Network Recovery Following Natural Disasters. *Journal of Urban Planning and Development*, *133*(1). https://doi.org/10.1061/(asce)0733-9488(2007)133:1(82)

Keck, D., Patel, H., Scolaro, A. J. ., Bloch, A., and Ryan, C. (2010). Accelerating Transportation Project and Program Delivery: Conception to Completion. In *Accelerating Transportation Project and Program Delivery: Conception to Completion*. https://doi.org/10.17226/14405

Kersting, R., Arendt, L., Bonowitz, D., Comerio, M., Davis, C., Deierlein, G., and Johnson, K. J. (2021). Recommended Options for Improving the Functional Recovery of the Built Environment. *Special Publication (NIST SP) – 1254*. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1254.pdf

Kijewski-Correa, T., and Robertson, I. (2018). StEER: Structural Extreme Event Reconnaissance network: Palu earthquake and tsunami, Sulawesi, Indonesia Field Assessment Team 1 (FAT-1) Early Access Reconnaissance Report (EARR). *Tech. Rep., StEER.*

Learning from Earthquakes (LFE) – Operations, v.2. (2015). https://www.eeri.org/wp-content/uploads/EERI-LFE-Operations-V2-approved-2015-12-08.pdf

Lockwood, S., O'Laughlin, J., Keever, D., and Weiss, K. (2005). Emergency Transportation Operations: Resources Guide for NCHRP Report 525, Volume 6. *Naational Academies of Sciences, Engineering, and Medicine*.

Luco, N., Garrett, B., and Hayes, J. (2015). New "Risk-Targeted" seismic maps introduced into building codes. *National Earthquake Hazards Reduction Program*, *June*, 1–3.

Maguire, F. (2009). Guide to asset management part 6: bridge performance. *Sydney: Austroads*.

Manual for GEER Reconnaissance Teams, v.4. (2014). http://www.geerassociation.org/media/files/Important

Marcelo, D., House, S., and Raina, A. (2018). Incorporating Resilience in Infrastructure Prioritization: Application to Japan's Road Transport Sector. *The World Bank*.

Murphy, R. R. (2019). Use of Small Unmanned Aerial Systems for Emergency Management of Flooding. *Federal Highway Administration Tech Brief.*

Nakanishi, Y. J., and Auza, P. M. (2015). *Interactive Training for All-Hazards Emergency Planning, Preparation, and Response for Maintenance and Operations Field Personnel (No. Project 20-05 (Topic 44-12))*.

O'Connor, J. S. (2010). *Post-Earthquake Bridge Inspection Guidelines. Final Report for NYSDOT. Project No. C-06-14. October*.

Oklahoma Dept. of Transportation. (2016). *Post-Earthquake Bridge Inspection Manual*.

Oklahoma Dept. of Transportation. (2017). *Post-Earthquake Response Plan for Oklahoma's Bridges*.

Olsen, M. J., Barbosa, A., Burns, P., Kashani, A., Wang, H., Veletzos, M., and Tabrizi, K. (2016a). *Assessing, Coding, and Marking of Highway Structures in Emergency Situations, Volume 2: Assessment Process Manual (No. Project 14-29)* (Vol. 2).

Olsen, M. J., Barbosa, A., Burns, P., Kashani, A., Wang, H., Veletzos, M., and Tabrizi, K. (2016b). *Assessing, Coding, and Marking of Highway Structures in Emergency Situations, Volume 3: Coding and Marking Guidelines (No. Project 14-29)* (Vol. 3).

Olsen, M. J., Barbosa, A., Burns, P., Kashani, A., Wang, H., Veletzos, M., and Tabrizi, K. (2016c). *Guidelines for Development of Smart Apps for Assessing, Coding, and Marking Highway Structures in Emergency Situations (No. NCHRP Project 14-29)*.

Orabi, W., El-Rayes, K., Senouci, A., and Al-Derham, H. (2009). Planning post-disaster reconstruction efforts of damaged transportation networks. *Building a Sustainable Future – Proceedings of the 2009 Construction Research Congress*. https://doi.org/10.1061/41020(339)116

Peeta, S., Sibel Salman, F., Gunnec, D., and Viswanath, K. (2010). Pre-disaster investment decisions for strengthening a highway network. *Computers and Operations Research*, *37*(10). https://doi.org/10.1016/j.cor.2009.12.006

Prendergast, L. J., Limongelli, M. P., Ademovic, N., Anžlin, A., Gavin, K., and Zanini, M. (2018). Structural health monitoring for performance assessment of bridges under flooding and seismic actions. *Structural Engineering International*, *28*(3). https://doi.org/10.1080/10168664.2018.1472534

Reed, D. A., and Wang, J. (1993). *An Emergency Response Plan for Bridge Management. Report No. WA-RD 289.1.Washington Department of Transportation*.

Seo, J., Hu, J. W., and Lee, J. (2016). Summary Review of Structural Health Monitoring Applications for Highway Bridges. *Journal of Performance of Constructed Facilities*, *30*(4). https://doi.org/10.1061/(asce)cf.1943-5509.0000824

SPUR. (2009). *The Resilient City: What San Francisco Needs from its Seismic Mitigation Policies*.

Stone, H., D'Ayala, D., and Wilkinson, S. (2017). The use of emerging technology in post-disaster reconnaissance missions. *EEFIT Report*.

USDOT. (2014). *FHWA Order 5520*.

Utah Dept. of Transportation. (2017). *Chapter 5: Emergency Response Plan, Bridge Management Manual*.

Veletzos, M., Panagiutou, M., Restrepo, J., and Sahs, S. (2008). Visual inspection and capacity assessment of earthquake damaged reinforced concrete bridge elements (No. CA08-0284). *California. Dept. of Transportation. Division of Research and Innovation*, *November*.

Wartman, J., Berman, J. W., Bostrom, A., Miles, S., Olsen, M., Gurley, K., Irish, J., Lowes, L., Tanner, T., Dafni, J., and Others. (2020). Research needs, challenges, and strategic approaches for natural hazards and disaster reconnaissance. *Frontiers in Built Environment*, *6*, 182.

Werner, S. D., Cho, S., Taylor, C. E., Lavoie, J.-P., Huyck, C. K., Chung, H., and Eguchi, R. . (2006). Redars 2 methodology and software for seismic risk analysis of highway systems. *Report MCEER-06-SP08, Buffalo NY: Multidisciplinary Center for Earthquake Engineering Research, March.*