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Resilience of Rural Communities and Transportation Networks to Hazards: Functionality Recovery of Network Components

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16. Abstract

Roadways and bridges are susceptible to damage from natural and non-natural hazards, such as earthquakes, hurricanes, fires, and age-related deterioration. As these systems are essential for transportation networks and community well-being, understanding their restoration timeline after hazards is crucial for community resilience. This research aimed to gather insights from approximately 1000 county engineers in the United States through an online survey, presenting various damage scenarios and cases. The survey sought feedback on immediate actions, traffic closure strategies, and the impact of changing structural parameters. Results revealed that the majority of immediate action responses involved repairing or replacing components or bridges, with varying timeframes for completion. Partial closures mainly included load and lane restrictions, each with specific timelines. Complete closure preferences leaned towards a fully open option during recovery, with other alternatives being less favored and having shorter timeframes.

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Abstract

Roadways and bridges are vulnerable to damage from both natural and non-natural hazards. Examples of natural hazards include earthquakes, hurricanes, and floods, while non-natural hazards encompass factors like fire, age-related deterioration, and vehicular collisions. These hazards can result in various types and degrees of damage to these crucial transportation infrastructures. Any significant damage to roadways and bridges has the potential to impact communities, as they play a vital role in facilitating the movement of people and goods within transportation networks.

The restoration timeline for recovering critical facilities is a crucial aspect of community resilience, as it guides the prioritization of construction efforts during the post-hazard phase. To address this, our research aimed to gather feedback from county engineers across the United States to identify trends and proposed timelines for recovery. For this purpose, an online survey was designed, incorporating a variety of cases and scenarios. These scenarios included both existing cases from literature and new cases generated by the authors. Each case was accompanied by descriptions of different damage levels. The survey was then distributed to approximately 1000 county engineers for their expert input.

The survey aimed to collect valuable comments and information pertaining to immediate actions for the damage infrastructure and the impacts to traffic. While only a handful of cases could be presented within the survey, questions were included to gauge the impact on immediate actions and traffic provided differences in structural parameters. The results indicate that the majority of immediate action responses involved repairing or replacing components or bridges. The timeframes for these actions varied, ranging from a few days for repairs to approximately two years for bridge replacements, as evident from the collected data. In terms of partial

closures, load and lane restrictions were the most commonly selected options, with specific timelines assigned to each. Regarding complete closure options, the preference leaned towards the fully open option during the recovery process, while other alternatives were less favored and assigned shorter timeframes.

Chapter 1 Introduction

Rural areas are home to the large majority (68%) of all lane-miles in the United States and are critical in the national transportation network connecting major population centers and ports as well as exporting critical agricultural products throughout the nation [1]. Despite the importance of rural areas to the national transportation network and the national economy, rural transportation has several unique challenges including substantially higher roadway fatality rates and poorer transportation infrastructure conditions compared to their more urban counterparts [1]. While it is apparent that collisions and other hazards can damage or potentially destroy a bridge or roadway, the impact can be quite far-reaching and result in disconnected travel routes, detours and increased travel times, and increased emergency response time. In the face of uncertain future hazards, it is imperative that transportation networks are resilient—defined as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" [2]. While resilience is actively considered in various aspects of transportation [e.g., 3 – 4], the unique challenges and attributes of rural areas that contribute to its resilience are currently unknown and there is a critical need to understand rural transportation resilience and to develop rural resilience strategies.

The National Academy of Sciences defines resilience as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" [2]. As such, the resilience of transportation systems must consider not only the immediate impact of a hazard but the recovery of the system, including anticipated repairs and the timeline to full functionality. While substantial research has been conducted to understand the immediate impact or damage to a bridge or roadway due to various hazards [5 – 7], relatively few studies have focused on the restoration of functionality. Existing functionality relationships for bridges and roadways are limited to short-term (e.g., 1-7 days) impacts, specific natural hazards (e.g., earthquakes), distinct functionality levels, and urban areas [8 – 10].

1.1 Research Objectives

The foremost methodology for developing functionality relationships is through surveys due to the lack of empirical reconnaissance data, which tend to focus on the immediate aftermath rather than the longitudinal recovery. The most comprehensive effort on this front, by Misra et al. [11], surveyed state Department of Transportation officials to develop statistics on anticipated functionality restoration for various natural hazards with a response rate of 24. The relatively low response rate did not provide sufficient information for a statistical relationship to be developed. Furthermore, a substantial percentage of lane-miles in the US fall under the purview of counties, which are likely to have markedly different restoration than those under state jurisdiction. In addition, non-natural hazards such as vehicular collision and/or fire were not considered. The long-term goal of this research is to reduce the negative consequences of vehicular crashes and other hazards to the rural transportation network by increasing the resilience of individual components, such as bridges and roadways. The primary objective of this project is to quantify the functionality restoration of bridges and roadways in rural areas in the aftermath of non-natural and other hazards, such that the resilience of rural transportation networks can be studied and ultimately enhanced.

1.2 Research Approach

This study was designed as a survey-based investigation. To gather valuable insights, an online survey was distributed to approximately 1000 county engineers across the United States. The survey aimed to collect their expert opinions on presented damage cases, which were categorized into roadways and bridges. The survey included a set of questions divided into three categories: immediate action, traffic closure, and parameter changes. These questions were generated in various formats, such as multiple-choice options, estimation of time (in days), and an open-ended text box for additional ideas or comments.

1.3 Research Organization

This report consists of several chapters that aim to provide a comprehensive understanding of the study. Chapter 2 focuses on the literature review, highlighting previous studies conducted in the field. In Chapter 3, the methodology employed for conducting the survey in this research is described in detail. Chapter 4 presents the results and analysis derived from the collected data. The data is categorized based on different damage levels and cases, with the primary objective of determining the restoration time required for roadways and bridges after a hazard event. Chapter 5 presents the conclusions and outlines future work.

Chapter 2 Literature Review

Transportation resilience has become an increasingly important subject among researchers nationwide in recent years. While some studies have investigated the immediate impact or damage to bridges or roadways caused by various hazards [e.g., 5 – 7], limited attention has been given to the restoration of functionality, which is the main focus of this project. This chapter provides a comprehensive literature review on this topic. Initially, it discusses the various definitions of "resilience" from the literature as proposed by different researchers and government agencies, with a specific emphasis on its application to transportation. Subsequently, available resilience frameworks are reviewed, followed by an examination of past studies and existing functionality relationships for transportation components, including bridges and roadways. The chapter concludes with a concise synthesis and identification of key knowledge gaps within this area.

2.1 Definition of resilience

The initial step in examining community resilience involves defining the concept of "resilience". Numerous researchers across various disciplines and fields have put forth definitions for resilience (refer to tTable 2.1). Notably, Koliou et al. [9] and Zhou et al. [10] have provided widely cited definitions of resilience in the literature. Among the various descriptions, Bruneau et al. [11] have specifically focused on resilience in the context of natural hazards, such as earthquakes. This definition of resilience encompasses four key aspects: (1) robustness, which refers to the ability to endure a specific level of stress without experiencing functional loss; (2) redundancy, which pertains to the degree of substitutability among elements and systems; (3) resourcefulness, which relates to the capability of identifying problems, setting priorities, and mobilizing resources; and (4) rapidity, which involves the capacity to promptly address priorities and accomplish objectives within appropriate timeframes [10].

An essential definition of the resilience concept can be found in Presidential Policy Directive 21 [12]. Furthermore, the US Department of Transportation has provided guidance on promoting resilient operations for the implementation of transformative, efficient, and cost-effective programs, which includes the most recent definition of resilience [13]. According to this guidance, resilience is defined as follows: “Resilience with respect to a project, means 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 to weather events or other natural disasters (23 U.S.C. 101 (a)(24)).”

Furthermore, the guidance provided by the US Department of Transportation includes a specific definition for “Resilience Improvement”. This term refers to “the use of materials or structural or nonstructural techniques, including natural infrastructure: (A) that allow a project (i) to better anticipate, prepare for, and adapt to changing conditions and to withstand and respond to disruptions; and (ii) to be better able to continue to serve the primary function of the project during and after weather events and natural disasters for the expected life of the project; or (B) that (i) reduce the magnitude and duration of impacts of current and future weather events and natural disasters to a project; or (ii) have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to current and future weather events or natural disasters (23 S.C. 176(a)(4)).”

Importantly, the resilience improvement plan highlights the need to incorporate other facilities, such as buildings and houses, in order to comprehensively assess the resilience of transportation infrastructure systems at the community level.

Table 2.1 Resilience definitions from literature [9] including newest ones

Source	Summary of resilience definition
Holling (1973)	The ability to store strain energy and deflect elastically under a specified loading condition without breakage or deformation
Gordon (1978)	The ability to store strain energy and deflect elastically under a specified loading condition without breakage or deformation
Timmerman (1981)	Resilience is the measure of a system's or part of the system's capacity to absorb and recover from occurrence of a hazardous event
Mileti (1999)	Ability to withstand an extreme natural event without suffering devasting losses, damage, diminished productivity, or quality of life, and without a large amount of assistance from outside the community
Adger (2000)	The capability of communities to resist external shocks to their social infrastructure
Paton and Johnson (2001)	The ability to pick up and utilize physical and economic resources for effective recovery following hazards
Folke et al. (2002)	Resilience for social-ecological systems is related to three different characteristics: (a) the magnitude of shock that the system can absorb and remain in within a given state; (b) the degree to which the system is capable of self-organization, and (c) the degree to which the system can build capacity for learning and adaptation
Bruneau et al. (2003)	The ability of social units (organizations, communities) to mitigate hazards, contain the effect of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes
Walter (2004)	Resilience is the capacity to survive, adapt, and recover from a natural disaster. Resilience relies on understanding the nature of possible natural disasters and taking steps to reduce risk before an evet as well as providing for quick recovery when a natural disaster occurs. These activities necessitate institutionalized planning and response networks to minimize diminished productivity, devastating losses, and decreased quality of life in the event of a disaster
Rose and Liao (2005)	The adaptive response to hazards in order to enable individual and communities to avoid potential losses
Adger et al. (2005)	The ability of systems following disasters to self-organize, with the capacity to learn from and adapt to disruptions

Source	Summary of resilience definition
UN/ISDR (2005)	Resilience is the capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures
Resilience Alliance (2007)	Ecosystem resilience is the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by different set of processes. Thus, a resilient ecosystem can withstand shocks and rebuild itself when necessary. Resilience in coupled social-ecological systems, the social systems have the added capacity of humans to learn from experience and anticipate and plan for the future.
Maguire and Hagan (2007)	Social resilience is the capacity of social entity e.g. group or community to bounce back or respond positively to adversity. Social resilience has three major properties, resistance, recovery, and creativity
Cutter et al. (2008)	The ability of a social system to respond and recover from disasters including those inherent conditions that allow the system to absorb impacts and cope with an event, post-event, and adaptive processes that facilitates the ability of the social system to recognize, change, and learn in response to a threat
Presidential Policy Directive 8 (PPD-8, 2011)	The ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies
National Academies (2012)	The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events
Presidential Policy Directive 21 (PPD-21, 2013)	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents
U.S Department of Transportation (2022)	Resilience with respect to a project, means 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 to weather events or other natural disasters (23 U.S.C. 101 (a)(24))

2.2 Resilience quantification and framework

The subsequent step in this study involves quantifying the defined resilience to enable comparisons of restoration conditions. In the United States, two main types of seismic restoration models have been developed. The first type focuses on estimating the probability of a bridge fully regaining its functionality based on its level of damage and the time elapsed since the earthquake event [14]. Conversely, there are restoration models that consider a range of functionality percentages. This means that even after repairing the bridge following a seismic event, the performance level may not necessarily match the pre-seismic event performance or reach 100% functionality [5], [15], [16]. The latter type of model has been widely employed by researchers to develop restoration models or quantify resilience. In this section, relevant studies are presented from the literature that explore the quantification of the resilience approach and provide a framework for its computation [11].

2.2.1 Bruneau et al. (2003)

This study aimed to provide a comprehensive and practical definition of resilience in the context of seismic hazards. Building upon this approach, Bruneau et al. [11] developed and proposed a quantified framework for resilience specifically tailored to seismic events. This framework encompasses multiple dimensions that can influence infrastructure systems, including technical, organizational, social, and economic aspects in relation to seismic occurrences. Moreover, it is based on three key seismic resilience characteristics: "Reduced failure probabilities", "Reduced consequences from failures", and "Reduced time to recovery". The mathematical formulation of resilience, as defined by Bruneau et al. [11], is as follows:

$$R = \int_{t_0}^{t_1} [100 - Q(t)]\, dt \tag{1}$$

Where $Q(t)$ is the functionality that is measured as a dimensionless function of time, t_1 is the control time of the system, and t_0 is the time of occurrence of an event. Figure 2.1 depicts a typical illustration of seismic resilience that shows the downgrading of performance and the evolution of recovery over time.

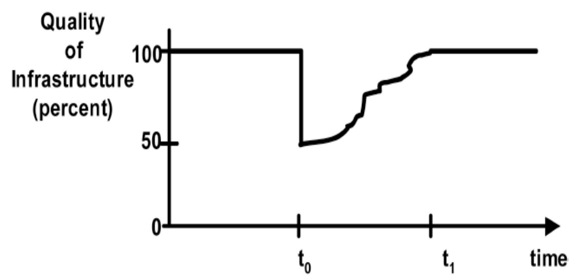


Figure 2.1 Seismic resilience measurement

The measurement of resilience in previous studies varied, with some researchers utilizing Eq. 1, which represents the area above the progress line in Figure 2.1. Conversely, other researchers opted to utilize the area beneath the line [6], [13]. Hence, the equation can be expressed as follows:

$$R = \int_{t_0}^{t_1} Q(t)/t_1 \, dt \tag{2}$$

2.2.2 Shinozuka et al. (2003)

This study conducted a probabilistic examination to assess the impact of bridge damage repair on improving transportation network performance following seismic events [14]. However, the study solely focused on evaluating the full performance of the bridge over time since the seismic event, neglecting the specific time required for repair and the target performance achieved during the repair process. The resilience analysis conducted in this study revealed that the systems exhibited considerable resilience, even in scenarios with low probabilities of moderate performance in degraded structures. Nevertheless, it is important to note that certain factors, such as the bridge type and characteristics like skew bridges and the number of spans, were not considered in these analyses.

2.2.3 Miles and Chang (2006) – Miles (2011)

Miles and Chang [17] advanced the concept of community resilience by incorporating various components, including households, neighborhoods, businesses, and infrastructure facilities. A distinctive aspect of their study was the establishment of connections among sectors, domains, scales, and recovery processes. This pioneering research stands as the first of its kind to systematically assign linkages between these elements. Moreover, the resilience framework they developed was grounded in empirical data. Leveraging this framework, they created a foundational software tool capable of capturing crucial variables and relationships within the resilience framework. Furthermore, they identified the type of empirical data required for assessing resilience within this framework.

Subsequently, an enhanced data-driven model was proposed to expand upon the framework developed by Miles and Chang by incorporating infrastructure loss and restoration data with temporal and spatial variations [18]. This simulation model, named ResilUS, integrates fragility curves to simulate loss and utilizes Markov chains to generate a recovery model over time. However, it is important to acknowledge certain limitations of this study. Firstly, the model lacks the capability to incorporate the relocation of households within the region of interest. Additionally, certain variables, such as the mitigation status of buildings, required modeling but could not be empirically validated due to limited available data. The author suggested utilizing this software primarily for educational and training purposes. Nevertheless, the software proved valuable in illustrating the interconnectedness of contributors in the recovery process.

2.2.4 Renschler et al. (2010)

Renschler et al. [7] introduced a comprehensive framework aimed at measuring community resilience, consisting of seven key aspects collectively referred to as PEOPLES. These dimensions encompass Populations and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital. Furthermore, this framework served as the foundation for the development of software designed to assess the ongoing resilience of a community [19]. To validate its effectiveness, the software was applied in a case study of the 2009 Italian earthquake, which resulted in substantial damage to numerous historical monumental buildings in L'Aquila. The software also establishes connections between the four resilience characteristics (robustness, redundancy, resourcefulness, and rapidity) and resilience dimensions spanning technical, organizational, societal, and economic realms. These interconnected relationships enable the measurement of resilience in the aftermath of seismic events. The availability of this software resulting from the study offers valuable support for decision-makers and planners.

2.2.5 Padgett and DesRoches (2007) - Bocchini and Frangopol (2012)

The analysis of resilience involves several steps, as depicted in Figure 2.2, including downgraded performance, idle period, and the recovery process. The recovery process illustrates the transition from a reduced performance level to an improved one. However, it is important to note that a return to full (100%) performance cannot be guaranteed. Among these steps, the analytical model for the restoration process can be represented in a stepwise formulation [5], [6], [20]. Importantly, this approach also allows for tracking the progress of repairs over time. The formula governing the timeline progress is as follows:

$$Q(t > t_0) = Q_r + H(t - t_0 - \delta_i)R\left(\frac{t - t_0 - \delta_i}{\delta_r}\right)(Q_t - Q_r) \tag{3}$$

Where $Q(t)$ is the functionality, t_0 is the time of earthquake occurrence, Q_r is the residual functionality after the event, $H()$ is the Heaviside step function, Q_t is the functionality reached at the end of recovery process, δ_i is the idle time between the occurrence of the seismic event and the starting of the recovery process, δ_r is the duration of the recovery, and $R()$ is the restoration function describing the profile of the recovery process that depends on the actual model used. Figure 2.2 illustrates the functionality process model by Equation 2. The key point in this model is related to recovery function or $R()$. Previous studies [15], [21] proposed a normal cumulative distribution function for $R()$ for highway bridges. It should be noted that this model is based on expert opinion survey data. This equation is formulated as:

$$R(t) = \Phi\left(\frac{t - m_{t,d}}{\sigma_{t,d}}\right) \tag{4}$$

Where $m_{t,d}$ is the mean of the restoration function for each one of the considered damage states, and $\sigma_{t,d}$ is the standard deviation for the mentioned function. Totally, restoration models are categorized as linear [16], stepwise [5], and lognormal [15] formulation.

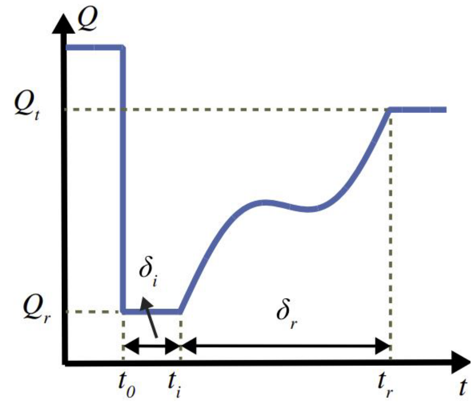


Figure 2.2 Functionality recovery model [20]

2.2.6 Ellingwood et al. (2016)

Multiple studies have been conducted to establish a model that accounts for the interplay between physical, social, and economic infrastructure systems [22]–[25]. The foundation of this model was the "Centerville Virtual Community", which served as a testbed for implementing interdisciplinary systems-based approaches in assessing community resilience [26]. It is important to highlight that this comprehensive framework can effectively consider the resilience of a community in the face of both earthquakes and tornado hazards. Additionally, Zhang and Nicholson [27] presented a decision framework based on this model. This decision framework aims to identify optimal strategies for minimizing economic losses and population dislocation.

The subsequent study took into account a constrained budget and unequal resource allocation for commercial and residential buildings. As a result, the proposed model enables the analysis and comparison of direct economic losses and immediate population dislocation in order to minimize these impacts. Additionally, the software demonstrated exceptional computational efficiency, completing a case study involving 15,000 structures across 16 different types and four code levels in just one millisecond.

2.2.7 Gardoni (2017)

Gardoni [28] devised a stochastic framework to assess the impact of deterioration and repair/recovery strategies on system performance, with a particular focus on reliability and resilience measures. Moreover, resilience equations were computed to determine the most suitable recovery strategy following a hazard event, given the current state of the system [29]. This study centers around the life cycle of an engineering system, incorporating both deterioration processes and repair/recovery procedures, which are influenced by multiple sources of uncertainty.

In a specific case study involving an RC bridge, the analysis encompassed the bridge's entire life cycle, considering deterioration resulting from corrosion and seismic damage. The interpretation of resilience highlighted the significant influence of deterioration processes on the probability of immediate failure. To mitigate long-term risks, frequent repairs were recommended to minimize the probability of the bridge being out of service.

2.2.8 Wang et al (2022)

This review article highlights the utilization of machine learning (ML) in evaluating the risk and resilience of structures and infrastructures [8]. The authors introduce and characterize six key features of ML that encompass significant aspects of resilience analysis. These features include the method employed, task type, data source, analysis scale, event type, and topic area. To provide a visual representation of the resilience framework and the implementation of ML within this process, Figure 2.3 illustrates the entire procedure.

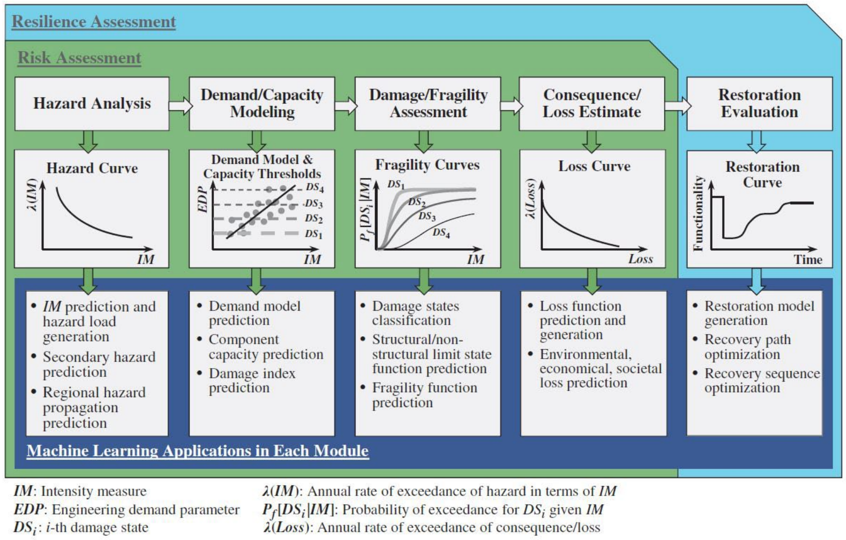


Figure 2.3 Risk and resilience frameworks and ML implementation [8]

The utilization of machine learning (ML) in each step of the resilience analysis process is depicted in the final row of Figure 2.3. It is important to note that the authors emphasized the significance of risk assessment as the foundation of resilience analysis, followed by restoration evaluation to monitor the time-evolution of functionality. ML techniques were then integrated into each step to enhance the modeling process.

Figure 2.4 provides detailed descriptions for all six features that contribute to resilience evaluation. The first three features categorize dominant ML approaches, while the last three features pertain to the characteristics of the study objects and problems being addressed.

(1) ML Method	(2) Task Type	(3) Data Source	(4) Analysis Scale	(5) Topic Area	(6) Event Type
1a) RS and evolvements	2a) Regression	3a) Field measurement	4a) Component	5a) Response prediction	6a) Operational condition
1b) ANN	2b) Classification	3b) Laboratory test	4b) Structure	5b) Capacity modeling	6b) Earthquake
1c) DL	2c) Clustering	3c) Computational simulation	4c) Regional/ network	5c) Damage/fragility assessment	6c) Wind
1d) SVM	2d) Dimensionality reduction			5d) Consequence/ loss estimate	6d) Landslide
1e) DT and ensembles	2e) Decision-making			5e) Restoration evaluation	6e) Flood/scour
1f) Others					6f) Wave/surge
					6g) Fire/wildfire

Figure 2.4 ML features and their descriptions in resilience analysis [8]

The authors acknowledged certain limitations associated with ML modeling, validation, and verification, particularly concerning insufficient data and sparsity. Additionally, understanding the underlying mechanisms of structures and infrastructures using ML models poses another challenge. However, the authors propose addressing these limitations by incorporating physics-guided ML modeling techniques.

2.3 Empirical/survey-based resilience studies

The analysis of roadways and bridges relies on two main sources: empirical data from past disruptions and expert opinion surveys. However, previous empirical studies have not adequately addressed critical aspects such as the duration of bridge closures or the timeline of recovery progress [1], [4], [30]–[34]. Furthermore, these studies have primarily focused on damage caused by earthquakes, hurricanes, tsunamis, and scour. This section provides an overview of the existing literature that have conducted resilience analyses using both empirical data and survey data.

2.3.1 Stearns and Padgett (2012)

In this research, the investigators presented empirical observations obtained through post-event reconnaissance following storm surges and wave loading during Hurricane Ike in 2008.

These observations revealed substantial damage to numerous roadways and bridges in the Houston and Galveston regions, with 53 bridges affected in particular [32]. Notably, rural timber bridges exhibited significant damage, underscoring the urgent need for retrofitting plans to ensure their structural integrity.

By comparing the empirical evidence from previous events with the damage inflicted by Hurricane Ike, the study confirmed the failure modes and identified potential retrofitting strategies. The author suggested that replacing the bridge decks with grated structures, which reduce surface erosion and minimize the impact on bridge abutments, could be an effective approach. Additionally, the proposal included replacing the entire timber bridge with a concrete counterpart, as this would enhance the community resilience in those areas.

2.3.2 Misra et al. (2020)

This investigation focused on the restoration process of roadways and bridges following a hazardous event. The study relied on expert opinions, gathered through an online survey that included photographs depicting the anticipated damage to roadways and bridges [35]. The survey was specifically designed for state engineers, who served as respondents. The primary objective of the research was to address the lack of information regarding bridge and roadway closures for different levels of damage. As a result, the survey questions encompassed both the type of traffic closure (complete or partial) and the severity of the damage (slight, moderate, severe). These considerations were crucial in formulating repair decisions and recommending appropriate actions, such as repair, component replacement, or bridge replacement.

The author further accounted for parameter changes in bridges to assess their impact on the survey responses. Specifically, factors such as the number of spans, span length, and pier height were considered as they could influence both traffic closure decisions and repair strategies. It is important to note that the survey was designed to capture damage resulting from earthquakes, hurricanes, and scour events. The findings underscored the significance of understanding the duration of traffic closures following hazard events, an area that had been largely overlooked in previous literature, particularly regarding roadways. However, the study encountered a limitation in terms of the number of responders or the size of the dataset, resulting in reported statistics with substantial variance or significant uncertainties. Building upon the input and primary outcomes of this study, a decision tree-based approach was developed to identify potential traffic restrictions and their corresponding timelines [36].

2.3.3 Mitoulis et al. (2021)

The objective of this research was to develop an expert-opinion-based recovery model for quantifying the flood resilience of bridges [37]. To gather the required information on flood damage, a survey was prepared and distributed among European experts. The survey primarily focused on the assessment of both spread and deep foundations of bridges. Furthermore, the research defined specific damage levels for various bridge components, including the foundation, bridge deck, bearing, abutment, wingwall, and backfill/approach slab. The restoration models developed in this study examined both the traffic capacity and structural capacity damage caused by floods.

The study revealed that expert opinions exhibited significant dispersion and were highly influenced by specific cases. Notably, there was substantial variation in their comments concerning idle (lag) time. However, a key finding derived from the expert feedback pertained to the direct and indirect costs associated with bridge closures. The responses indicated that the duration of traffic closure was approximately half of the time required for full restoration of bridge capacity. Consequently, the indirect costs outweighed the direct costs. The responses concerning slight and moderate damage were more aligned with prior literature. However, it is important to acknowledge that the study had limitations as it only included experts from Europe, thereby neglecting insights from professionals in other regions. It should be recognized that the duration of repairs depends on operator policies, resource availability, and financial conditions. The authors recommended employing Monte Carlo sampling or machine learning techniques to address uncertainties associated with the duration of restoration tasks.

2.3.4 Miner and Alipour (2022)

A recent empirical study addressed a significant gap in the literature by investigating the costs and damage incurred by bridges during inland floods [38]. This particular hazard had not received sufficient attention in previous research on various hazards. The study considered multiple types of damage, including scour, high water levels, debris accumulation, and abutment washout.

The cost data utilized in this research were derived from detailed damage inspection reports (DDIRs), which are crucial for state or local agencies to obtain supplemental funding through the FHWA ER program. The findings of this study can assist authorities in identifying vulnerable bridges based on their condition ratings, enabling them to implement effective resilience and recovery programs. It is important to note that the cost estimation models presented in this paper were based on Iowa transportation data collected over a specific time period. Therefore, caution should be exercised when applying these models to other regions with different construction and design practices.

2.3.5 Misra and Padgett (2022)

This research introduced a framework aimed at quantifying the resilience of rail-truck intermodal freight transportation networks under regional natural hazards [39]. The primary focus of the study was to determine the restoration timeline for these networks, thus assessing their resilience. A key advantage of the novel restoration model presented in this research was its ability to establish a connection between physical damage and functionality, while incorporating uncertainties into the modeling of recovery progress. These uncertainties encompassed both intrinsic aspects of damage and decisions regarding network closures.

Furthermore, the framework was designed to facilitate the economic evaluation of the resilience model. Integration of the framework and algorithms within INCORE, an open-source tool for community resilience modeling, allowed for a seamless linkage between the two [40]. This project is part of a series of resilience studies conducted on infrastructure networks [41].

2.3.6 Williams et al. (2022)

This study focuses on conducting a risk assessment to evaluate the impact of tsunamis on coastal infrastructures [42]. The evaluation process employs empirical models to assess the effects of tsunamis on coastal infrastructure systems. Specifically, the study models the closure and restoration timeline of road transportation in response to a hypothetical tsunami hazard. Collaboration between researchers and practitioners was instrumental in developing a deterministic tsunami impact scenario. The case study conducted in Christchurch, New Zealand involved multiple sessions with the Christchurch City Council to validate, refine, and contribute to the inputs, methods, and results, as highlighted by the authors.

The results of the study aim to draw attention to key findings and provide recommendations for various stakeholders. These recommendations encompass areas such as land-use management, emergency response planning, infrastructure component mitigation, and network mitigation. Additionally, the findings indicate that in the case study area, the road network may experience the exposure of approximately 16% of roads and 5% of bridges to tsunami hazards. These results contribute valuable insights for stakeholders involved in coastal infrastructure planning and risk management.

2.4 Synthesis and knowledge gaps

The previous sections provided an overview of the accomplishments in the assessment of resilience for transportation networks, highlighting the quantification of resilience evaluation and its application across various studies.

Furthermore, it was noted that the majority of these studies primarily focused on hazards such as earthquakes, and to a lesser extent, hurricanes, scour, and floods. However, non-natural hazards were not adequately considered in these investigations. Additionally, the survey-based studies conducted thus far were based on expert opinions without explicit confirmation of their involvement in the repair or recovery of infrastructures. Consequently, these gaps serve as the impetus for the current research, which aims to address and present findings in the subsequent chapters.

Chapter 3 Survey overview

This project is designed to gather valuable technical information from county engineers through an expert-opinion survey. The transportation networks, including roadways and bridges, are susceptible to various natural hazards such as earthquakes and hurricanes. These hazards can cause damage to roadways and bridges through scouring and surface washout, among other effects. Additionally, these transportation facilities are prone to accidents like vehicular collisions and fire events. Furthermore, these structures undergo deterioration over time due to aging. As a result, it becomes necessary to implement traffic closures and rehabilitation measures, or even consider replacement or rebuilding, in order to restore the transportation systems to their previous level of performance. The purpose of the survey is to collect engineers' insights and comments based on their experiences, which will assist decision-makers in planning and organizing efforts to achieve community resilience.

The survey is divided into two general sections: roadways and bridges, each consisting of seven parts. Each part is designed to address specific aspects related to damage resulting from hazards or age-related effects. For roadways, these parts cover seismic and hurricane damage, while for bridges, they encompass seismic and hurricane damage, scour damage, age deterioration damage, fire damage, and vehicular collision damage. Each part includes a variety of questions to ensure the comprehensive collection of all necessary information. These questions pertain to factors such as the decision regarding traffic closure (none, partial, complete), the type of closure for partial and complete closures, the duration of the closure, and repair recommendations specifically tailored for bridges.

The survey was created using the online platform called Qualtrics and distributed to respondents. The survey was sent to county engineers as they are directly involved in the management of roadways and bridges. County engineers are responsible for the maintenance and repair of many roadways and bridges, making them a suitable target audience for this survey. The survey was delivered to county engineers via email, containing a web link for them to access and respond to the survey.

The contact information of approximately 1000 county engineers was collected to the best extent possible and the survey was subsequently sent to them. The authors conducted a comprehensive search across all 50 states to gather the contact details of county engineers. In some cases, county engineers had their own websites which provided essential information such as email addresses and telephone numbers. However, not all county engineers had a web presence, so the state county engineer association and the National Association of County Engineers (NACE) were utilized to obtain the contact information of the remaining county engineers. Despite these efforts, the accessibility limitations resulted in the contact information of county engineers being restricted to approximately 1000 individuals. In compliance with the requirements of the Institutional Review Board (IRB) at the University of Nebraska-Lincoln, the identification of survey respondents was not recorded.

A total of 41 individuals participated in the survey across all parts. The distribution of responders in each part is presented in Table 3.1. However, it is worth noting that all respondents who attempted the roadway-seismic damage section indicated that they lacked experience in this particular field. As a result, they were redirected to the end of that section, resulting in no answers being entered. A similar situation occurred in the bridge-seismic and hurricane damage section, where two respondents lacked relevant experience. Additionally, some responses were either incomplete or abandoned by the participants. These include one responder's answer for bridge-vehicular collision damage, one responder for bridge-seismic and hurricane damage, two responders for bridge-scour damage, one responder for bridge-fire damage, and one responder for roadway-hurricane damage.

Table 3.1 Responders in each part of survey

Survey part	Number of responders
Roadway – seismic damage	3
Roadway – hurricane damage	6
Bridge – seismic & hurricane damage	3
Bridge – scour damage	9
Bridge – age deterioration damage	10
Bridge – fire damage	4
Bridge – vehicular collision damage	6

3.1 Survey details

The survey was designed to address crucial questions aimed at developing a plan for community resilience. Previous studies [35], [37] have identified a gap in the literature regarding the traffic closure strategy in response to different levels of damage. Therefore, this survey emphasizes the exploration of closure options and restoration durations. While the complete online version of the survey is available in the appendix, this section provides additional information to accompany each question or section in the survey, offering further clarity and guidance.

3.1.1 roadways

In the roadway category for the seismic and hurricane parts, images were extracted from a previous expert-opinion study [35]. The initial question posed to participants involved selecting a traffic closure option. The available options included none, partial closure, and complete closure. Subsequently, depending on the chosen option and if road closure was deemed necessary, further questions were presented. For partial closure, respondents were asked to specify the type of closure, such as lane restriction, speed restriction, or load restriction. Once the type of partial closure was selected, participants were asked to provide the estimated number of days required for each closure type to be restored. Similar questions were posed for the complete closure option, but with different choices for the type of closure. These options included opening the road with traffic restrictions in place, lifting lane restrictions, lifting speed restrictions, lifting load restrictions, and fully opening the road to traffic. Another question was included to assess any changes in respondents' decisions regarding restoration time based on parameter variations in roadways. These parameter changes encompassed factors such as the road classification being interstate, arterial, or local, the doubling or halving of the number of traffic lanes, and the pavement mixture being concrete without an asphalt overlay.

It is important to highlight that for each question, a designated section was provided for responders to share any additional comments they may have. In the seismic part of the survey, a total of three cases were included, comprising pictures of damaged roads, corresponding descriptions, and the aforementioned related questions. Similarly, the hurricane part consisted of four cases, following a similar pattern of including relevant pictures and corresponding questions.

3.1.2 bridges

The second category of the survey focuses on bridges and addresses questions related to damage caused by natural or non-natural hazards. The pictures included in this category were sourced from various literature references [35], [43]–[45], social media platforms [46]–[48], and data collected by the investigators.

For each case within this category, the survey commenced by inquiring about recommended actions. This question aimed to identify immediate actions that should be taken in response to the observed damage. The available response options were: no action, repair, replace the component, replace the bridge, or not sure. Additionally, a separate space was provided within this question to gather estimated repair or replacement times in days for the component or the entire bridge.

The remaining questions followed a similar pattern as those in the roadway category. However, there were some variations in the options regarding the effects of parameter changes on restoration time. These options were tailored to specific scenarios or cases. It is important to note that the pictures included in the bridges section were characterized as scenarios depicting seismic and hurricane damage. Each scenario encompassed images of the bridge deck and the damaged components.

The questions were carefully designed to gather relevant information for the development of a restoration timeline. Clear instructions were provided at the beginning of each section to ensure that respondents could understand and answer the questions accurately.

It is important to note that the responses to these questions can be influenced by various external factors specific to each site. Decisions regarding restoration timeframes and repair strategies can vary depending on the effects of local conditions. Factors such as the significance of the bridge or roadway segment, site accessibility, resource availability and allocation across the network, as well as unforeseen delays in repair activities, may impact these decisions [35].

To address this issue, certain assumptions were made in the survey concerning roadways and bridge conditions, as well as local financial and facilities awareness. These assumptions were derived from a previous study [35], and they serve as a foundation for understanding and analyzing the responses obtained in the survey. The following assumptions were made regarding roadways and bridges in the survey:

1. Prior to the occurrence of the hazard, it is assumed that both bridges and roadways were fully operational and in service.

2. Sufficient funds and necessary resources are available to conduct repair activities without encountering any unforeseen delays.

3. All bridges and roads have good site accessibility. This assumption allows respondents to disregard additional delays caused by poor accessibility, which could potentially impact repair times (e.g., in the case of a water crossing bridge).

4. All roadways and bridges are considered to have an equally high level of priority for restoring operations.

5. Adequate site analysis has been conducted to assess the extent of damage and facilitate the estimation of quantities.

These assumptions serve as a basis for the survey, enabling respondents to provide their insights and considerations within the given framework.

3.2 Damage levels descriptions

As previously mentioned, the survey includes visual representations of damaged roadways and bridge components. To provide clarity regarding the level of damage to the survey respondents, descriptions were included for each case that corresponds to one or more pictures. In this section, Table 3.2 presents the photographs along with their respective damage descriptions for each case across all parts and categories of the survey.

Table 3.2 Cases or scenarios used in the survey with their associated damage level descriptions

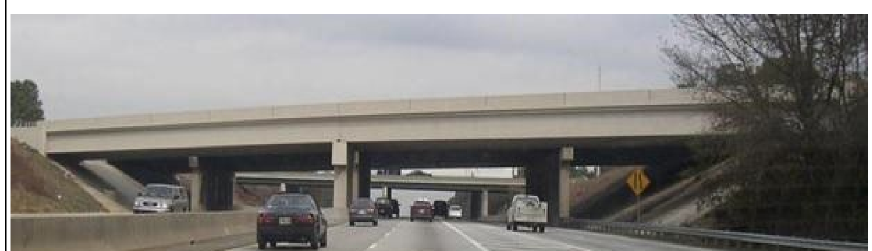
Category - part	Case or scenario	Damage descriptions	Photos
Roadway – seismic damage	#1	Settlement or ground offset of ~ 1 inch. Crack propagated along the width of road and passed all lanes.	
	#2	Settlement or ground offset of ~ 6 inches. Crack does not propagate beyond one lane.	
	#3	Settlement of roadway by over a foot. Crack does not propagate beyond one lane.	 

Roadway – hurricane damage	#1	Visible damage due to surface layer loss and base failure in the form of pothole formation, alligator cracking in the longitudinal direction and heaving on asphalt pavement.	 
	#2	Visible damage due to surface layer loss on asphalt pavement leading to exposed base material.	 
	#3	Washout of asphalt surface and part of the base material over a stretch of 100 feet and a width of approximately one lane.	 
	#4	Complete washout of asphalt surface and base material over a stretch of 100 feet and a width of approximately one lane.	

<table>
<tr><td rowspan="3">Bridge – seismic & hurricane damage</td><td rowspan="2">#1</td><td colspan="2">3-span simply supported concrete girder bridge supported on 14 feet tall multi-column bents.
The bridge carries a 4 lane 2-way road

with moderate traffic intensity.</td><td colspan="2"></td></tr>
<tr><td>Pullout of anchor bolt from elastomeric bearing to longitudinal deck movement by ~ 2 inches</td><td>Minor cracking in column (crackwidth ~ 0.01 inches)</td><td>
</td><td></td></tr>
<tr><td>#2</td><td colspan="2">3-span simply supported steel girder bridge supported on 14 feet tall multi-column bents.
The bridge carries a 4 lane 2-way road with moderate traffic intensity.</td><td colspan="2"></td></tr>
</table>

Bridge – seismic & hurricane damage		Settlement of abutment-approach interface by ~ 5 inches	Complete loss of support at bearing leading to unseated deck	Flexural failure column rebars			
	#3	3-span simply supported steel girder bridge supported on 14-foot bents. The bridge carries a 4 lane 2-way road with moderate traffic intensity.					
		Slightly tilted rocker bearing without damage to deck					

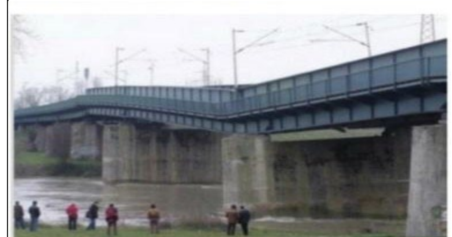
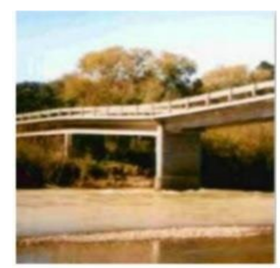
Bridge – seismic & hurricane damage	#4	3-span continuous concrete box girder bridge supported on 14-foot columns integral with superstructure. The bridge carries a 4 lane 2-way road with moderate traffic intensity.	
		Minor cracking at abutment wingwall (crackwidth ~ 0.01 inches)	
		Minor spalling in column	
	#5	3-span continuous concrete girder bridge supported on 14-foot multi-column bents. The bridge carries a 4 lane 2-way road with moderate traffic intensity.	

<table>
<tr><td rowspan="3">Bridge – seismic & hurricane damage</td><td></td><td colspan="2">Minor spalling in column</td><td colspan="2"></td></tr>
<tr><td rowspan="2">#6</td><td colspan="2">3-span simply supported steel girder bridge supported on 14-foot multi-column bents.
The bridge carries a 4 lane 2-way road with moderate traffic intensity.</td><td colspan="2"></td></tr>
<tr><td>Slightly tilted rocker bearing without damage to deck</td><td>Flexural cracking

(crackwidth ~ 0.04 inches)</td><td></td><td></td></tr>
</table>

<table>
<tr>
<td rowspan="3">Bridge – seismic & hurricane damage</td>
<td rowspan="2">#7</td>
<td colspan="2">3-span simply supported concrete girder bridge supported on 14-foot multi-column bents.
The bridge carries a 4 lane 2-way road with moderate traffic intensity.</td>
<td colspan="2"></td>
</tr>
<tr>
<td>Pull out of anchor bolts in elastomeric bearing</td>
<td>Extensive shear cracking
and spalling in column</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#8</td>
<td colspan="2">3-span simply supported steel girder bridge supported on 14-foot multi-column bents.
The bridge carries a 4 lane 2-way road with moderate traffic intensity.</td>
<td colspan="2"></td>
</tr>
</table>

Bridge – seismic & hurricane damage		Minor cracking at abutment wingwall (crackwidth ~ 0.01 inches)	Toppled rocker bearing leading to vertical deck offset by above 6 inches	Flexural failure of column rebars			
	#9	3-span simply supported concrete girder bridge supported on 14-foot single-column bents. The bridge carries a 4 lane 2-way road with moderate traffic intensity.					
		Minor cracking at abutment (crackwidth ~ 0.01 inches)	Sliding of elastomeric bearing wingwall leading to ~ 5 inches transverse deck offset	Shear failure of column			

Bridge – scour damage	#1	Scour at abutment leading to piles being exposed. Assume piles of length 50 feet and depth of scour to be about 5 feet. The soil is non-cohesive.	 
	#2	Scouring at pier base leading to exposed foundation. Assume piles of length 50 feet and depth of scour to be about 3 feet. The soil is non-cohesive.	 
	#3	Scouring leading to settlement at pier. The soil is non-cohesive.	 

Bridge – fire damage	#1	The fire caused damage to the north face of the bridge pier steel elements of the superstructure, bridge deck, and utilities attached to the bridge. Specific damage: 1. Out-of-plane buckling of the steel girders (max ~ 2.48 in). 2. Spalling and cracking of the concrete deck and pier. 3. Steel discoloration.	
	#2	The fire caused spalling of pier and the concrete cover is removed.	
	#3	The superstructure of bridge collapsed due to fire damage.	

Bridge – age deterioration damage	#1	The concrete cover is removed, and the rebar is visible. There is evidence of rebar corrosion.	  
	#2	The steel girder near the pin-and-hanger connection is notably corroded.	
	#3	The steel girders at bearing are highly corroded.	  
	#4	The steel girders are highly corroded near the bearing and there is significant evidence of material loss.	  

Bridge – vehicular collision damage	#1	The collision caused slight damage to the concrete surface. The flexural cracks propagated along one-third length of the column at the bottom.	
	#2	The collision with the pier caused failure in the 30-inch diameter pier. The bridge did not collapse because of impact.	
	#3	A tractor-trailer collided with the bents supporting the first and second spans, causing collapse of both spans.	

In the roadway category, specifically in the seismic damage part, all three cases presented a range of damage levels, from minor damage such as a ground offset of approximately one inch to severe damage, including settlement of around one foot.

A similar pattern was observed in the hurricane damage section of the roadway category, which consisted of four cases. The first case exhibited insignificant damage, characterized by the formation of potholes in certain sections of the roads and alligator cracking in the longitudinal direction. In the second case, visible damage was evident, with surface loss of the road and exposure of underlying base materials. The third case demonstrated significant washout of the road surface and removal of base material over a distance of 100 feet. Finally, the fourth case depicted complete washout of the road surface and removal of base material, indicating severe or extensive damage to roadways caused by hurricane hazards.

The bridge category consisted of five parts that encompassed both natural and non-natural hazards. The first part focused on seismic and hurricane damage, and it was comprised of nine scenarios. Instead of presenting a photo of a specific damage instance, these scenarios considered various aspects of bridges. A side view photo of the bridge was provided to showcase the overall system, materials, and supports of the bridge. Subsequently, photos of damaged components were shown to illustrate different types of damage.

The selection of damaged components aimed to cover a range of possible damage levels. Examples of these components included pull-out of anchor bolts from elastomeric bearings, cracks, abutment settlement, loss of support, failure of column rebars, and spalling. These visual representations were included to elicit comments from county engineers regarding repair recommendations and restoration timelines for the identified damages.

Within the bridge category, there was another part dedicated to scour damage. This part showcased three cases to demonstrate the effects of scouring on different bridge locations. The first case described exposed piles, while the second case depicted an exposed foundation. Lastly, the third case displayed settlement resulting from scouring on a bridge.

In the fire damage part of the bridge category, examples of both steel and concrete bridges were provided. These two materials exhibited different types of damage due to fire. The first case presented a steel bridge with out-of-plane buckling of the steel girder and discoloration. Fire can lead to spalling and the removal of protective cover, exposing rebars. Furthermore, fire can potentially cause the collapse of the superstructure. Therefore, the second and third cases illustrated these conditions in the context of bridge fires.

Age deterioration was addressed as part of the bridge category. In concrete bridges, age deterioration could be shown through cover removal and rebar corrosion, which was depicted in the first case. In steel bridges, corrosion of steel connections and steel girders were illustrated in the second, third, and fourth cases.

The final part of the survey focused on vehicular collision damage to bridges. Three cases were presented to demonstrate different levels of damage. The first case showed slight damage to a bridge column resulting from a truck collision. The second case depicted the failure of a pier, and the third case presented severe damage in the form of the total collapse of the superstructure due to a tractor-trailer collision.

In conclusion, the hazard description sections covered all possible damage and their associated locations, ensuring that respondents had ample information to analyze the effects of hazards on roadways and bridges.

Chapter 4 Results and analysis

This chapter presents the comprehensive findings obtained from county engineers, organized into three main categories: immediate action (for bridges), traffic closure (for both bridges and roadways), and parametric changes (for both bridges and roadways). The results are primarily presented in tables, indicating the number of respondents for each action or parameter and the corresponding repair or restoration time. Furthermore, the survey included comment boxes, providing an opportunity for respondents to share additional feedback or comments beyond the predefined format and questions. The following sections will outline and discuss these findings in detail.

4.1 Immediate actions (for bridges)

This section focuses on the recommendations for repair decisions as immediate actions for bridges. As mentioned earlier, there are five specific actions identified to encompass all necessary quick responses: no action, repair, replace the component, replace the bridge, and not sure. These actions have been selected to demonstrate and encompass a comprehensive range of possible immediate actions in bridge repair decision-making.

4.1.1 Age deterioration damage to bridges

Table 4.1 presents the repair decision table for age deterioration damage on bridges. The table shows responses from nine participants for all damage levels except for RH1, which had ten participants. It was expected that the dominant recommendation for the RH1 damage level would be repair, given the cover removal of beams and columns. However, it is worth noting that one responder suggested the replacement of the component instead. Similar patterns were observed for RH2 and RH3, but with a greater contribution of the replacement of the component option. These damage levels involved corrosion in the steel girder near the pin-and-hanger connection and at the bearing. While the county engineers' comments predominantly leaned towards repair, there was an increased inclination towards recommending the replacement of the component for corrosion at the bearing (RH3). This recommendation aligns with the anticipation that the girder may fail, leading to potential deck slippage or collapse. Consequently, these cases may necessitate more robust strategies or actions beyond mere repair. On the other hand, RH4, which exhibited significant corrosion and material loss near the bearing, raised serious concerns among responders, leading to a preference for the options "Replace the component" or even "Replace the bridge".

Table 4.1 Immediate action recommendation - Age deterioration damage of bridges

Damage level	Repair decision (number of respondents)					
	Total	No action	Repair	Replace the component	Replace the bridge	Not sure
RH1	10	-	7	1	-	2
RH2	9	-	6	2	-	1
RH3	9	-	4	4	-	1
RH4	9	-	-	5	4	-

Table 4.2 provides an overview of the repair times associated with each damage level. While there are two instances where the repair times for RH1 are unknown or listed as zero, the repair times for the other actions range from 5 to 150 days. Similarly, the repair time ranges for RH2, RH3, and RH4 are 3 to 150 days, 5 to 150 days, and 10 to 240 days, respectively. As anticipated, the repair time is higher for the last damage level (RH4) due to the recommendation for the replacement of either the component or the entire bridge.

Table 4.2 Repair time for each damage level – Age deterioration damage of bridges

Damage level	Repair decision	Repair time (days)
RH1	Repair	5, 60, 5, 9, 30, 150, 5
RH1	Not sure	0, 30
RH1	Replace the component	-
RH2	Repair	3, 30, 3, 5, 10, 60
RH2	Replace the component	-, 150
RH2	Not sure	-
RH3	Repair	60, 10, 150, 10
RH3	Not sure	-
RH3	Replace the component	5, -, 30, 45
RH4	Replace the component	10, -, 5, 20, 30,
RH4	Replace the bridge	-, 240, 90, -

4.1.2 Fire damage to bridges

The fire damage levels of bridges have been classified into three categories: RH1, RH2, and RH3. Table 4.3 presents the number of respondents for each fire catastrophe damage level. In this section, two respondents provided answers for each damage level. Notably, there is a variation in the selection of actions among the responders. One responder chose the "Repair" option, while the other responder opted for the "Replace the bridge" option. This dispersion in action selection highlights different perspectives and preferences among the respondents in addressing fire damage to bridges.

Table 4.3 Immediate action recommendation - Fire damage of bridges

Damage level	Repair decision (number of respondents)					
	Total	No action	Repair	Replace the component	Replace the bridge	Not sure
RH1	2	-	-	1	-	1
RH2	2	-	1	-	1	-
RH3	2	-	-	1	1	-

Table 4.4 provides the repair times associated with the repair decisions for fire damage, as mentioned in the table. The responses indicate that the responders were certain about the need for either replacing or repairing the damage levels (with the exception of one instance in RH1). However, there was uncertainty regarding the duration of the repairs. Notably, the replacement of components for the RH1 damage level received a recommendation of four months, whereas the repair decisions for the remaining damage levels were suggested to be completed in less than 50 days.

Table 4.4 Repair time for each damage level - Fire damage of bridges

Damage level	Repair decision	Repair time (days)
RH1	Replace the component	120
RH1	Not sure	-
RH2	Replace the bridge	-
RH2	Repair	15
RH3	Replace the bridge	-
RH3	Replace the component	45

4.1.3 Scour damage to bridges

For this natural hazard, three levels of scour damage were established. Table 4.5 displays the responses received from the participants across all damage levels, totaling seven responses. The findings indicate that the responders had a clear understanding of the damage when making decisions regarding immediate action, as no one selected the "Not sure" option. The primary recommendations were focused on repair options. However, for the RH3 damage level, which involved settlement at the pier of bridges due to scouring, replacement recommendations were provided for either the entire bridge or specific components. Additionally, one or two respondents also confirmed the replacement options for RH1 and RH2. Overall, it appears that the responders possessed greater experience and expertise in dealing with scour damage compared to other types of damage.

Table 4.5 Immediate action recommendation - Scour damage of bridges

Damage level	Repair decision (number of respondents)					
	Total	No action	Repair	Replace the component	Replace the bridge	Not sure
RH1	7	-	4	2	1	-
RH2	7	-	6	-	1	-
RH3	7	-	-	2	5	-

The repair time results in this section revealed a broad range of durations, as almost all respondents provided repair times for each damage level, with the exception of one individual (refer to Table 4.6). For the RH1 damage level, responses varied around one month for both repair and replacement options, except for two outliers reporting repair times of 3 and 270 days, respectively. In the case of RH2, one respondent recommended a one-year duration for bridge replacement, while others indicated repair times ranging from a couple of days to one or two months. As anticipated, the restoration time for RH3 exhibited a wider range, spanning from one month to approximately two years, reflecting the time-consuming nature of replacement efforts.

Table 4.6 Repair time for each damage level - Scour damage of bridges

Damage level	Repair decision	Repair time (days)
RH1	Repair	30, 10, 3, 30
RH1	Replace the component	40, 21
RH1	Replace the bridge	270
RH2	Repair	60, 5, 3, 4, 60, 30
RH2	Replace the bridge	365
RH3	Replace the component	120, 60
RH3	Replace the bridge	365, -, 365, 800, 365

4.1.4 Vehicular collision damage to bridges

The final part of the bridge damage section pertains to vehicular collision, involving three damage levels as outlined in Table 4.7. A total of five responses were received for this category. Notably, none of the responders selected the "Not sure" or "No action" options, and their answers were distributed between repair and replacement options.

For the RH1 damage level, where there was slight damage to the concrete surface of the column of the pier caused by a collision, all responders recommended repair. This response was in line with expectations given the nature of the damage.

In the case of RH2, where failure was observed in the column of the pier, responses were divided between replacement of the component with one repair recommendation and replacement of the entire bridge (with one responder suggesting this course of action). This variation in responses can be attributed to the severity of the damage and different perspectives among the respondents.

Lastly, all five responses for the RH3 damage level indicated the need for the replacement of the bridge. This unanimous recommendation is attributed to the collapse of the bridge deck resulting from the collision.

Overall, the responses demonstrate a range of repair and replacement recommendations based on the specific damage levels caused by vehicular collision.

Table 4.7 Immediate action recommendation – Vehicular collision damage of bridges

Damage level	Repair decision (number of respondents recommending)					
	Total	No action	Repair	Replace the component	Replace the bridge	Not sure
RH1	5	-	5	-	-	-
RH2	5	-	1	3	1	-
RH3	5	-	-	-	5	-

Table 4.8 presents the durations associated with immediate actions for vehicular collision damage. In the RH1 damage level, the repair times range from 10 to 180 days. For RH2, the duration varies between 20 and 730 days. Notably, RH3 requires a longer duration due to the recommended replacement of the entire bridge, with the range spanning from 120 to 730 days. It is worth mentioning that one responder did not provide a specific time recommendation.

These findings highlight the diverse repair durations that can be anticipated for different damage levels resulting from vehicular collisions. The varying timeframes reflect the complexity and extent of the required repairs, underscoring the importance of carefully considering the specific circumstances of each damage level.

Table 4.8 Repair time for each damage level - Scour damage of bridges

Damage level	Repair decision	Repair time (days)
RH1	Repair	30, 20, 10, 10, 180
RH2	Repair	20
RH2	Replace the component	60, 30, 60
RH2	Replace the bridge	730
RH3	Replace the bridge	-, 120, 120, 240, 730

4.1.5 Seismic and hurricane damage to bridges

In this part, only one responder selected the “Not sure” option, and there are no other responses from others.

4.2 Traffic closure (for roadways and bridges)

This section presents the data on traffic closures obtained from county engineers, covering both roadways and bridges. The concept of closure was defined and categorized into two types: partial closure, which includes three options (lane restriction, speed restriction, and load restriction), and complete closure, which offers two additional options (fully open and open with restriction). This classification enabled the responders to choose the most suitable recommendation for traffic closure. Consequently, the results of the survey are outlined below.

4.2.1 Roadways – Hurricane damage

Regarding hurricane damage to roadways, the survey received responses from four or five participants. As indicated in Table 4.9, it was anticipated that responders would select the "None" option for the RH1 and RH2 damage levels, given the presence of minor surface damage to the road. However, for the RH3 and RH4 damage levels, most responders recommended complete closure, while a few experts suggested partial closure. This trend aligns with expectations, as the first two damage levels involved cracks and pothole damage, while the latter two levels represented more severe damage, such as washouts in certain sections of the roadways.

Table 4.9 Traffic closure for each damage level – Hurricane damage of roadways

Damage level	Number of respondents	Traffic closure		
		None	Complete closure	Partial closure
RH1	5	4	-	1
RH2	5	5	-	-
RH3	5	-	3	2
RH4	4	-	3	1

Regarding the recommended partial closure responses, lane restriction emerged as the most common option, while load restriction had the fewest selections (refer to Table 4.10). Notably, for the RH1 damage level, only one responder indicated a lane restriction of five days. This responder also noted that the specified duration depends on the severity of base damage and whether there was damage to any culverts beneath the road (if any). In contrast, one of the responders for the RH3 damage level suggested a two-month duration for both lane and speed restrictions. Furthermore, the responder for the RH4 damage level recommended all types of restrictions and estimated a one-week timeframe for completing the restoration of the damaged roadway.

Table 4.10 Partial closure of hurricane damage - Roadways

Damage level	Time to complete restoration (days)		
	Lane restriction	Speed restriction	Load restriction
RH1	5	-	-
RH3	60	60	-
RH3	-	-	-
RH4	7	7	7

The findings for the complete closure aspect of hurricane damage to roadways were somewhat limited, as some responders either did not provide an answer or did not mention the restoration time (refer to Table 4.11). Among the two available responses for the RH3 damage level, a restoration time of approximately one month was proposed for all types of restrictions, although one responder suggested a direct full opening after this time. The responder who suggested a one-month restoration time added that this duration is contingent upon the safe shoring up of the waterside. Similarly, a similar trend was observed for the RH4 damage level, with restoration times ranging from two to four months to recover the roadways from the extreme damage level. Additionally, the responder who proposed a 90-day duration noted that the restoration time depends on the shoring and armoring of the waterside.

Table 4.11 Complete closure of hurricane damage - Roadways

Damage level	Time to complete restoration (days)				
	Open with restrictions	Lane restriction lifted	Speed restriction lifted	Load restriction lifted	Fully open
RH3	-	-	-	-	-
RH3	-	-	-	-	30
RH3	30	40	40	40	40
RH4	60	60	60	60	120
RH4	-	-	-	-	-
RH4	-	-	-	-	90

4.2.2 Roadways – Seismic damage

Nobody answered traffic closure questions for the seismic damage part of this survey due to lack of experience of responders in this type of damage.

4.2.3 Bridges – Age deterioration damage

Traffic closure responses for age deterioration damage of bridges garnered a significant number of replies, as depicted in Table 4.12. Across all four damage levels, the majority of selected responses fell into the categories of "None" and "Partial closure". In the case of the RH1 level, all responses, except for one, indicated no action. For the RH2 level, there were five responses for none, two responses for complete closure, and two responses for partial closure. In the case of the RH3 level, there were three responses for none and six responses for partial closure. Finally, for the RH4 level, a notable number of responses indicated both complete and partial closure, with four and three responses, respectively.

Table 4.12 Traffic closure for each damage level – Age deterioration damage of bridges

Damage level	Number of respondents	Traffic closure		
		None	Complete closure	Partial closure
RH1	10	9	-	1
RH2	9	5	2	2
RH3	9	3	-	6
RH4	9	2	4	3

The restoration timeline for bridges affected by age deterioration damage exhibited a relatively narrow range of durations, ranging from approximately 5 to 30 days, with one exception of 150 days, as presented in Table 4.13. In the case of the RH1 level, only one responder provided a response, recommending a 10-day period for the removal of lane restrictions. For the RH2 level, two responders indicated restoration durations of either 10 or 25 days for all restrictions, with the exception of speed restriction, which was mentioned without a specified duration by a responder. One responder who suggested a 10-day restoration duration for all restrictions inquired about the connections in the RH2 case, specifically investigating the presence of any other links and estimating the level of corrosion.

Table 4.13 illustrates that responders suggested restoration times ranging from 5 to 30 days for various types of restrictions in the RH3 case. However, one responder specified a 150-day duration for load restriction. Another responder who proposed a 10-day restoration duration for all restrictions highlighted the practicality of using UHPC encasements in this scenario. Furthermore, a responder recommending a 150-day load restriction noted that post-inspection would require a structural analysis to determine the load-carrying capacity.

Lastly, for the RH4 level, two responders proposed restoration durations of either 10 or 30 days for all restrictions, with the exception of speed restriction, which was mentioned without a specified duration by a responder.

Table 4.13 Partial closure of age deterioration damage - Bridges

Damage level	Time to complete restoration (days)		
	Lane restriction	Speed restriction	Load restriction
RH1	10	-	-
RH2	25	25	25
RH2	10	-	10
RH3	5	5	5
RH3	8	-	8
RH3	10	10	10
RH3	30	-	30
RH3	-	-	150
RH4	10	10	10
RH4	30	-	30

In terms of complete closure recommendations, it is noteworthy that one responder for the RH2 level believed that a restoration period of two months would be sufficient for fully restoring the damaged bridge. In contrast, another responder suggested a duration of five months for the bridge to be fully open (as depicted in Table 4.14). The latter responder also provided a comment stating that the damage appeared to be fracture critical, and previous fracture-critical structures have failed. Therefore, they recommended full closure as the safest option until repairs could be made.

For the RH4 level, experts mentioned restoration timelines of eight months or one year. However, it should be noted that one responder expressed the opinion that 20 days would be sufficient to fully open the bridge to the public in the RH4 damage level. Furthermore, a responder who recommended a restoration time of one year made a crucial comment regarding a general assumption of the survey. This person highlighted that the funding availability, contractor availability, and availability of materials dictate the duration of closure. It is important to note that these resources (financial and human resources) were assumed to be equally available in the survey.

Lastly, a responder who selected the complete closure option but did not provide a specific duration for any restrictions mentioned that accurately estimating the requested information based on the limited pictures is not possible. This responder emphasized that more extensive information, such as site access and the extent of damage, is needed. The responder noted that based on their observations, the pin and hanger appeared to have chipped paint, and the beam at the bearing still had packed rust. Therefore, determining at least the removal of the packed rust is not possible without further information.

Table 4.14 Complete closure of age deterioration damage - Bridges

Damage level	Time to complete restoration (days)				
	Open with restrictions	Lane restriction lifted	Speed restriction lifted	Load restriction lifted	Fully open
RH2	-	-	-	-	150
RH2	60	60	60	60	60
RH4	-	-	-	-	20
RH4	365	365	365	365	365
RH4	-	-	-	-	240

4.2.4 Bridges – Fire damage

Regarding traffic closure recommendations for fire damage on bridges, the number of responses received was limited. There were two responses for each of the three damage levels, as indicated in Table 4.15. It is worth noting that the majority of the selections leaned towards the complete closure option.

Table 4.15 Traffic closure for each damage level – Fire damage of bridges

Damage level	Number of respondents	Traffic closure		
		None	Complete closure	Partial closure
RH1	2	1	1	-
RH2	2	-	1	1
RH3	2	-	2	-

The only responder in partial closure with lane restriction mentioned that the bridge can be removed after 15 days for the RH2 damage level, as shown in Table 4.16.

Table 4.16 Partial closure of fire damage - Bridges

Damage level	Time to complete restoration (days)		
	Lane restriction	Speed restriction	Load restriction
RH2	15	-	-

When examining the complete closure recommendations for fire damage in Table 4.17, we observe a few specified restoration durations. One responder suggested a timeframe of one day to remove restrictions for the RH1 damage level. Another responder proposed a restoration duration of four months for the RH2 damage level. Additionally, one responder selected 45 days as the estimated timeframe for the RH3 damage level to be fully opened to the public for utilization.

Table 4.17 Complete closure of fire damage - Bridges

Damage level	Time to complete restoration (days)				
	Open with restrictions	Lane restriction lifted	Speed restriction lifted	Load restriction lifted	Fully open
RH1	1	-	-	-	-
RH2	-	-	-	-	120
RH3	-	-	-	-	-
RH3	-	-	-	-	45

4.2.5 Bridges – Scour damage

The results depicted in Table 4.18 reveal that complete closure was the most frequently selected option for addressing scour damage to bridges. A total of seven responders provided answers across all three damage levels. For the RH1 level, six responders recommended complete closure, while one responder chose none as their preferred option. In the case of the RH2 level, the responses were more evenly distributed among partial closure (two responses), complete closure (two responses), and none (three responses). It is noteworthy that six out of seven responders suggested complete closure as the preferred option. However, one responder suggested partial closure for the RH3 case.

Table 4.18 Traffic closure for each damage level – Scour damage of bridges

Damage level	Number of respondents	Traffic closure		
		None	Complete closure	Partial closure
RH1	7	1	6	-
RH2	7	3	2	2
RH3	7	-	6	1

Two county engineers recommended a partial closure approach for addressing scour damage in the RH2 level. The suggested restoration timeframe ranged from three to five days, primarily focusing on the removal of speed and load restrictions. Conversely, in the case of the RH3 damage level, one responder proposed a significantly longer restoration duration of one year. These findings are presented in Table 4.19.

Table 4.19 Partial closure of scour damage - Bridges

Damage level	Time to complete restoration (days)		
	Lane restriction	Speed restriction	Load restriction
RH2	-	3	3
RH2	-	5	-
RH3	-	365	365

In the complete closure section, the restoration time for the RH1 damage level varied from 2 to 270 days. Two responders exclusively considered the option of fully opening the bridge, while the remaining respondents considered all restriction options. One responder, whose opinion is presented in the first row of Table 4.20, suggested that the load restriction might need to be in place for a longer period, taking into account factors such as concrete curing time. Additionally, another responder recommended a restoration time of 21 days, noting that this duration is subject to various factors including bureaucracy, crew availability, and material availability. The 270-day timeline stood out as longer compared to the other suggestions for the RH1 case, and the respondent mentioned the possibility of closing the bridge to all traffic. This responder also highlighted that the construction timeline would depend on the availability of the new bridge plans.

For the RH2 damage level, a responder with a recommended restoration time of 60 days for full opening expressed uncertainty regarding whether the piles have bearings based on the provided pictures. This person emphasized that a comprehensive evaluation of the structural integrity requires full bridge closure initially. Ultimately, the recommended restoration durations increase from RH1 to RH2, ranging from 60 to 400 days. Similarly, for the RH3 damage level, the recommended durations escalate further, ranging from 60 to 800 days.

Table 4.20 Complete closure of scour damage - Bridges

Damage level	Time to complete restoration (days)				
	Open with restrictions	Lane restriction lifted	Speed restriction lifted	Load restriction lifted	Fully open
RH1	35	40	40	40	40
RH1	-	-	-	-	30
RH1	10	10	10	10	10
RH1	2	3	3	3	4
RH1	21	21	21	21	21
RH1	-	-	-	-	270
RH2	330	365	365	400	400
RH2	-	-	-	-	60
RH3	-	-	-	-	120
RH3	100	100	100	100	100
RH3	-	-	-	-	60
RH3	365	365	365	365	365
RH3	-	-	-	-	800
RH3	365	365	365	365	365

4.2.6 Bridges – Vehicular collision damage

As anticipated, the responses from the county engineers regarding traffic closure for bridges affected by vehicular collision largely leaned towards complete or partial closures. Only two respondents opted for no closure in the case of the RH1 damage level, as indicated in Table 4.21.

Table 4.21 Traffic closure for each damage level – Vehicular collision damage of bridges

Damage level	Number of respondents	Traffic closure		
		None	Complete closure	Partial closure
RH1	5	2	1	2
RH2	5	-	2	3
RH3	5	-	5	-

The partial closures responses in Table 4.22 show that all selected restrictions involve lane and load. Regarding the RH1 damage level, the recommended restoration durations were either 10 or 20 days. On the other hand, for the RH2 damage level, three responders suggested restoration timelines of 20, 30, and 60 days.

Table 4.22 Partial closure of vehicular collision damage - Bridges

Damage level	Time to complete restoration (days)		
	Lane restriction	Speed restriction	Load restriction
RH1	20	-	-
RH1	10	-	10
RH2	30	-	30
RH2	20	-	20
RH2	60	-	60

In terms of complete closure, as depicted in Table 4.23, one responder recommended a restoration duration of 180 days to fully restore the damaged bridge in the RH1 level. Furthermore, the responder noted the importance of evaluating whether the concrete encapsulating pile was the only damage or if the pile itself had been damaged. If the pile was indeed damaged, the repair process would be more extensive.

For the RH2 level, restoration durations of 50 and 730 days were recommended for the removal of various restrictions. Additionally, the responder who proposed the longer duration of

730 days noticed that the superstructure of the bridge had also suffered damage as a result of the impact to the pile.

Lastly, since the RH3 level involved the collapse of bridge spans and is categorized as significant damage, the restoration time ranged from 120 to 730 days.

Table 4.23 Complete closure of vehicular collision damage - Bridges

Damage level	Time to complete restoration (days)				
	Open with restrictions	Lane restriction lifted	Speed restriction lifted	Load restriction lifted	Fully open
RH1	-	-	-	-	180
RH2	50	50	50	50	50
RH2	-	-	-	-	730
RH3	-	-	-	-	120
RH3	120	120	120	120	120
RH3	-	-	-	-	120
RH3	240	240	240	240	240
RH3	-	-	-	-	730

4.2.7 Bridges – Seismic and hurricane damage

In this damage category, it is noteworthy that only one responder opted for complete closure for the RH1 damage level. However, the responder did not provide a specific duration for the corresponding restrictions in their recommendation.

4.3 Parameter changes (for roadways and bridges)

This section of the survey aimed to gather responses from county engineers to capture the diverse range of bridges and roadways affected by different parameters that can influence the extent of damage and the time required for recovery or restoration. It is important to mention that this survey operated under the assumption that resources for restoration, including economic, material, and human resources, were available at a consistent level. No respondents provided answers for the seismic and seismic/hurricane damage to roadways and bridges in this part of the survey. As a result, the expert comments and recommendations obtained from other parts of the survey are presented below.

As depicted in Table 4.24, the majority of responses across all parameters indicated no change in restoration time. However, it is worth noting that some responders suggested a decrease in the duration, particularly for variations in road classification. Interestingly, the findings reveal that an increase in restoration time was observed for interstate road classification, with three responders reporting a time increase of more than twice the original duration. A similar trend was observed for arterial classification, with three responders indicating a time increase of approximately 1.5 times. Furthermore, the type of pavement mixture was identified as another factor that could impact the recovery timeline, with three responders suggesting an increase of about 1.5 times. Importantly, one responder mentioned that in some cases, replacing with Portland Cement Concrete (PCC) could expedite the restoration process, depending on the availability of Hot Mix Asphalt (HMA).

Table 4.24 Parameter changes for hurricane damage of roadways

Parameter variation	Total number of responses	Decreased	Unchanged	~ 1.5 times longer	~ 2 times longer	> 2 times longer
The road classification is interstate	9	3	3	-	-	3
The road classification is arterial	9	3	3	3	-	-
The road classification is local	9	1	8	-	-	-
Number of traffic lanes is doubled	9	-	7	2	-	-
Number of traffic is halved	9	2	6	-	-	1
Pavement mixture is concrete (No asphalt overlay)	9	-	5	3	-	1

According to Table 4.25, the majority of responders recommended no change in restoration time when considering variation in parameters related to age deterioration damage. However, a few respondents suggested an increase in duration by approximately 1.5 or 2 times when these parameters are altered. For instance, an increase in the number of traffic lanes (doubling) was found to have an impact of approximately twice the original duration, as confirmed by six responders. A similar trend was observed when the number of spans was changed. Additionally, a couple of responders recommended allocating extra time (around 1.5 times) in cases where span length, number of spans, column height, and number of traffic lanes are high. Furthermore, some responders provided additional comments. In the RH2 case, one responder noted that the precast concrete girders would likely not be fracture critical. Regarding the RH3 case, the same responder mentioned that insurance coverage would not necessarily be provided assuming all spans had deteriorated bearings. Finally, another responder highlighted that the limited pictures in the RH4 case make it impossible to accurately estimate the required information and emphasized the need for additional details.

Table 4.25 Parameter changes for age deterioration damage of bridges

Parameter variation	Total number of responses	Decreased	Unchanged	~ 1.5 times longer	~ 2 times longer	> 2 times longer
Span length is doubled	17	-	14	1	2	-
Number of spans is doubled	17	-	10	2	5	-
Column height is increased by ~ 20%	17	-	13	4	-	-
Number of traffic lanes is doubled	17	-	7	4	6	-

According to Table 4.26, changes in bridge parameters in the fire damage part of the survey indicated that the duration of recovery generally increased by approximately 1.5 or 2 times the normal timeframe as the factors or parameters increased. However, there were still respondents who suggested no change in restoration time even when the factors were higher than before.

Table 4.26 Parameter changes for fire damage of bridges

Parameter variation	Total number of responses	Decreased	Unchanged	~ 1.5 times longer	~ 2 times longer	> 2 times longer
Span length is doubled	5	-	2	2	1	-
Number of spans is doubled	5	-	2	1	2	-
Column height is increased by ~ 20%	5	-	3	1	1	-
Number of traffic lanes is doubled	5	-	2	2	1	-

In contrast to other damage categories, the scour damage category showed a range of responses from experts regarding the effect of increased parameters on restoration time, as seen in Table 4.27. While most of the results indicated no change in time with increasing parameters, there were instances where the time either decreased or increased. It is important to note that this damage category included two additional parameters to account for variation in soil types and pier length. The responses indicated that in the case of change to a cohesive soil type, the recovery or restoration time could potentially decrease, as indicated by five respondents. One responder provided an additional comment, stating that the bridge in the RH3 case is similar to a major arterial due to its long length and may be prone to other failures.

Table 4.27 Parameter changes for scour damage of bridges

Parameter variation	Total number of responses	Decreased	Unchanged	~ 1.5 times longer	~ 2 times longer	> 2 times longer
Span length is doubled	17	-	10	3	2	2
Number of spans is doubled	17	-	10	4	2	1
Pier height is increased by ~ 20%	17	-	7	8	2	-
Number of traffic lanes is doubled	17	-	4	5	5	3
The soil is cohesive	17	5	12	-	-	-
The pier length is doubled	17	-	8	7	2	-

The analysis of parameter changes in vehicular damage to bridges revealed that most of the increased parameters led to an increase in the recovery timeline, approximately 1.5 to 2 times longer. However, it is important to note that the "unchanged" option remained dominant, with responders suggesting that no increase or decrease in restoration time was necessary (see Table 4.28). Furthermore, one responder provided an additional comment, stating the need to investigate whether any movement in the pile had impacted the superstructure in the RH1 case.

Table 4.28 Parameter changes for vehicular collision damage of bridges

Parameter variation	Total number of responses	Decreased	Unchanged	~ 1.5 times longer	~ 2 times longer	> 2 times longer
Span length is doubled	13	-	10	2	1	-
Number of spans is doubled	13	-	9	1	3	-
Pier height is increased by ~ 20%	13	-	5	7	1	-
Number of traffic lanes is doubled	13	-	9	1	3	
Superstructure is made of precast concrete girders	13	-	10	3	-	-

Chapter 5 Conclusions

This research study aimed to determine the restoration timeline for roadways and bridges affected by natural and non-natural hazards. An online survey was developed, consisting of various cases and scenarios presented through pictures and accompanying damage descriptions. The survey was distributed to approximately 1000 county engineers and professionals across the United States, targeting their expertise and insights.

The findings of the study highlighted that age deterioration and scour damage were particularly evident and recognizable to the responders, likely due to the visible nature of the damage and their experience in assessing such situations. In contrast, seismic damage to both roadways and bridges received minimal responses, indicating a potential knowledge gap or lack of expertise in this area.

Furthermore, the majority of responses regarding immediate actions focused on repair or replacement of components and bridges. The timeframe for these recommended actions varied, with repair options typically requiring a few days, while the replacement of bridges could take up to two years, as indicated by the collected data.

The analysis of traffic closure data revealed that the extent of closure, whether partial or complete, varied based on the level of damage. Among partial closure options, load and lane restrictions were the most commonly selected choices, with corresponding timelines assigned. On the other hand, when considering complete closure options, the "fully open" alternative was predominantly chosen as the benchmark for the recovery process, while other closure options received less attention and assigned timelines.

Furthermore, the study incorporated parameters related to the type of bridge or roadway and construction conditions to provide insights applicable to a broader range of infrastructures.

Overall, the findings indicated that there was generally no significant need to adjust the assigned timelines based on these increased parameters or conditions, as compared to the presented cases and scenarios. However, it is worth noting that a few respondents did suggest either an increase or decrease in the restoration timeline, although these instances were less common.

While acknowledging the limitations of the available data, the collected information can still serve as a valuable resource for decision-makers in predicting the duration of restoration and recovery efforts within their communities. By leveraging this data, decision-makers can effectively plan and allocate resources to meet the resilience goals of their respective areas. Furthermore, the data can contribute to the development of machine learning models at the community level. These models have the potential to enhance preparedness by enabling the anticipation and prioritization of rehabilitation measures prior to the occurrence of hazards, as well as streamlining the construction process in the aftermath of such events. Ultimately, these efforts aim to bolster community resilience and enhance overall disaster management strategies.

Chapter 6 References

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