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Identification of Resilience Dimensions and Development of a Decision-Making System to Measure the Resilience Level of Highway Networks

by

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Presented to the Faculty of the Graduate School of
The University of Texas at Arlington
in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT ARLINGTON

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DEDICATION

My parents

Md. Yunus Miah & Shaheen Akhtar

Who spend life building mine!

My husband

Md Asif Akhtar

Who believes in me even when I doubt myself!

My daughter

Maya Nahara Nipakhtar

Who never ceases to impress and encourage me!

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December 2021

NOMENCLATURE

USDOT	United States Department of Transportation
NCTCOG	North Central Texas Council of Governments
UTA	University of Texas at Arlington
DHS	Department of Homeland Security
CI	Critical Infrastructure
IRB	Institutional Review Board
FEMA	Federal Emergency Management Agency
DOT	Department of Transportation
FHWA	Federal Highway Administration
EFA	Exploratory Factor Analysis
KMO test	Keiser-Meyer-Olkin test
SEM	Structural Equation Model
χ^2	Chi-Square
df	Degree of freedom
RMSEA	Root Mean Square Residual
CFI	Comparative Fit Index
PNFI	Parsimonious Fit Index
S.E.	Standard Error
C.R.	Critical Ratio
IC	Influencing Factor
PC	Project Characteristics
RC	Roadway Characteristics
MC	Management Characteristics
RM	Resilience Measured

ABSTRACT

IDENTIFICATION OF RESILIENCE DIMENSIONS AND DEVELOPMENT OF A DECISION-MAKING SYSTEM TO MEASURE THE RESILIENCE LEVEL OF HIGHWAY NETWORKS

Thahomina Jahan Nipa

The University of Texas at Arlington, 2021

Supervising Professor: Dr. Sharareh Kermanshachi

Local as well as national economy and safety depend on the network characteristics of the transportation infrastructures. Destruction of transportation infrastructures causes the direct cost of the reconstruction as well as indirect cost due to loss of mobility. In addition, emergency response and recovery cannot be rendered if access to the affected community is hampered due to a damaged transportation network. Hence, researchers as well national and international organizations are focusing more on a resilience-based approach instead of a traditional recovery-based approach for the transportation infrastructures recently. As a result, there exist a high number of research articles that developed resilience measurement dimensions and models for such infrastructures. Being a relatively new topic in the field of transportation, a comprehensive model to measure the resilience of transportation infrastructure is yet to be developed. Moreover, developed dimensions are incoherent in meaning throughout the literature. Hence, there are a lot of opportunities to enhance the current literature of resilience analysis in transportation infrastructure by integrating different perspectives which are rarely studied. Such a perspective is addressing transportation resilience from the construction and management point of view. Moreover, characteristics of investment and funding which might have an impact on the level of resilience are also a rarely studied topic in transportation network resilience analysis. Therefore, this study aims to establish a list of transportation infrastructure resilience measurement dimensions. This study will also establish a decision-making tool to measure the resilience of the transportation infrastructures as well as determine the relationship of the dimensions with the rapidity of the infrastructures. To fulfill the aim of this study, a questionnaire `was developed based on a comprehensive literature review. Experts in transportation construction and reconstruction projects were chosen as the potential participants for this study and the survey was sent through electronic media. After a couple of reminder emails, 92 valid responses were collected. Collected data were analyzed qualitatively and quantitatively.

Statistically significant variables were determined from a total of 35 variables. It was found that there were 21 significant variables based on the criteria involvement in the reconstruction projects. The effect size of each of the 21 variables was determined and based on the effect size they were ranked and scored. It was found that having dedicated investment for future resilience enhancement activities while planning and investing for a new project is the most impactful on the level of resilience of the transportation infrastructure. The variable with the second most effect was the availability of previous disaster data of the roadway. The developed decision-making tool will provide a comparative value for the level of resilience for transportation infrastructures projects. In addition, to understand the impact of significant variables on the rapidity of the project, a model was developed. A sophisticated modeling technique, structural equation modeling (SEM), was used to develop the model to study the causal relationships of the variables with rapidity. Before performing modeling, exploratory factor analysis (EFA) was performed to group the variables into different components. Based on the literature, the hypothesis was made and introduced into the model in the SPSS AMOS. The model was analyzed, and the results are interpreted. It was found that, construct integrated assets has the maximum impact on the rapidity

of the transportation infrastructures. Having a railroad crossing integrated on the roadway will have higher possibility to retard the restoration activity of the transportation network by delaying the restoration of other integrated infrastructures.

The findings of this study will help decision-makers in prioritizing the projects based on their criticality in resilience level and support their decisions in investing and funding in the most critical transportation infrastructure projects. This study will also help in recognizing critical paths that contribute most to prolonging recovery time and slowing down the recovery speed of a transportation network after a roadway. It will also help practitioners in establishing proper strategies against the corresponding contributing delay factor to improve the resilience of the network.

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CHAPTER 1

INTRODUCTION

1.1. Background

The human community develops and thrives with the growth of the transportation system (Das, 2020). In a similar yet opposite manner, the human community highly suffers when the network characteristics of the transportation infrastructure get affected. A compromised transportation system has the potential to hamper national security and economy as well as community people's health and safety (Merschman et al, 2020; Nipa et al., 2022a). Community not only suffers from the direct cost of reconstruction when a transportation system gets affected but also suffers from indirect cost due to loss of mobility which ceases local businesses (Cox et al, 2011). Interdependency of transportation infrastructures with other critical infrastructures contributes to indirect loss greatly (Mikalsen et al., 2020). Another major drawback of a damaged transportation network is the loss of lifeline for rescuing and evacuating people and rendering first-aid help to the affected community (Mattson and Jenelius, 2015). The vast network characteristics of the transportation system make it vulnerable and easy prey to disruptive events (Mojtahedi et al., 2017; Miklasen et al., 2020). Moreover, most critical infrastructures including transportation infrastructures are costly and complex hence they are oftentimes utilized up to their maximum capacity which makes them vulnerable to disasters and disruptions (Das, 2020).

Global warming and global climate change are making climatic events unpredictable, and more frequent (Vajjarapu et al., 2020). Climatic events are becoming severe and intense which causing months long, even sometimes years-long destruction for critical infrastructures (CIs) like transportation infrastructures (Liu and McNeil, 2020; Safapour et al., 2020a; Kermanshachi et al., 2019). For example, Hurricane Irene of 2011 on the East Coast of the U.S damaged more than 500, 2000, and 200 miles respectively of highways, roadways, and railways which resulted in 56 deaths and around \$15.6 billion losses (Wan et al., 2018). After the Kobe earthquake in 1995, Japan suffered from the closure of rail, road, and port services for months as well as disruption in other critical infrastructures like electricity, telecommunication, water, and gas (Mojtahedi et al., 2017). Hurricane Harvey caused a flood which resulted in more than \$190 billion worth of loss in the region of Texas and Louisiana (Sun et al., 2020, Pamidimukkala et al., 2020a). Disasters also cause outstanding damage to the resources of the local community this hampers the capacity of the community to recover to its original state of functionality (Goidal et al., 2019; Westen, 2000). However, destruction by disaster is unevenly distributed throughout the region worldwide as well as within the local communities (Imperiale and Vanclay, 2021). Such uneven distribution of destruction depends on the vulnerability and resilience of the community (Fraser, 2021). A resilient system has the potential to reduce the destruction caused by the disaster as well as shorten the recovery time to regain functionality faster (Heaslip et al., 2009; Adepu et al., 2022).

Importance of transportation network in human prosperity, heightened negative impact of the destruction of such network, and the increased number of disasters making policymakers, practitioners, and researchers more and more interested in the issue of transportation network resilience (Imperiale and Vanclay., 2021; Safapour and Kermanshachi, 2021a, Rouhanizadeh and Kermanshachi, 2018). Resilience has become the key to keeping the major function of the transportation network which is moving people and goods from one place to another continuously (Titko et al., 2020). The current trend of research is more into focusing on mitigation-based philosophy which requires timely response and faster recovery from the disaster (Hosseini and

Barker, 2016). The traditional recovery-based approach is converting into a more resilient-based approach for transportation infrastructures (Cutter, 2016; Brummitt et al., 2012) which is also encouraging practitioners to consider severe events as the opportunity to build back better and increase the resilience of the structure (Imperiale and Vanclay, 2021).

The concept of resilience was first introduced by ecologists in 1973 and since then almost all the other application domains adopted this terminology in their related fields (Franchin and Cavalieri, 2015). Researchers, as well as national and international organizations, are prioritizing resilience over recovery in recent years (Wan et al., 2018; Rouhanizadeh and Kermanshachi, 2019a). Consequently, the concept of resilience is gaining rapid popularity and is being studied vigorously. Resilience has become an issue of national interest and governmental organizations like the Department of Homeland Security (DHS) are focusing on resilience and encouraging authorities under their jurisdiction to stay up to date regarding their related infrastructures resilience level to reduce risk and possibility of damage by the disaster (Faturechi and Miller-Hooks, 2014). Even though the concept of resilience is being studied for more than half a century, the transportation sector has integrated the concept of resilience only recently since 2009 (Wan et al., 2018). Yet, there exist numerous definitions, dimensions, models, and matrices to define and measure transportation infrastructure resilience. Dick et al. (2019) defined resilience as a system's capability to withstand foreseen and unforeseen disasters with minimum disruption in the functionality. Faturechi and Miller-Hooks (2014) developed four mathematical formulations in the context of transportation networks focusing on functionality, rapidity, recovery, and flexibility of resilient systems. Freckleton et al. (2012) developed a conceptual framework considering only the level of damage, redundancy, and rapidity of resilience. Mojtahedi et al. (2017) developed a model adopting Cox’s proportional hazards regression model by taking region, disaster type, and cost of the reconstruction as the dimensions to determine the rate of recovery in New South Wales, Australia. Liao et al., (2018) developed a model focusing on optimization of resource allocation for the transportation networks to enhance resilience. Turnquist and Vugrin, (2013) found that the resilience of a system is the combination of the absorptive, adaptive, and restorative capability of the system. Whereas absorptive capacity indicates the capacity to sustain disruption, adaptive capacity indicates the redundancy of the network and restorative capacity indicates the capacity of the system to restore to its original form with a reduced cost. Such capabilities can be provided with proper investment and funding. Hence, characteristics of funding and investments also have the ability to alter the resilience of a system.

Identification of proper dimensions under a comprehensive list of categories and modeling interrelationships among the dimensions has many benefits. Such a model will help researchers better understand the concept of resilience and how it is related to many factors that one must consider while dealing with critical infrastructures. Modelling resilience and the resilience influencing factors provides a support-system for the policymakers, practitioners, and decision-makers to enforce their decisions in practical field.

1.2. Problem statement

Transportation infrastructures are incorporating analysis of resilience with the aim of having the improved capability to withstand disruption resulting in rapid recovery after a disaster with minimal interruption in operation (Merchman et al., 2020). Resilience analysis helps in identifying risks beforehand and employing management strategies to attenuate the impact of identified risk against many disasters. Resilience study also enhances system safety and helps in an optimal distribution of funding and investment (Sun et al., 2020; Kermanshachi et al., 2021). Despite having many benefits of having resilient transportation infrastructure, researchers are still divided when it comes to quantifying transportation resilience, hence, current literature lacks in providing a well-understood comprehensive model to measure transportation resilience (Liao et al., 2018). One of the major reasons behind this disagreement is the lack of universal dimensions to measure the resilience of transportation infrastructures (Liu and McNeil, 2020). The existing dimensions are not consistent throughout the literature, and they are not adequate to interpret the performance of the infrastructures (Liu and McNeil, 2020). In addition, the complex nature of uncertainty and interconnectivity of the transportation infrastructures are also hindering in developing a comprehensive measurement model (Sun et al., 2020). The models that are currently existing in the literature incorporate traffic characteristics like origin-destination travel pattern (Das, 2020), as well as road characteristics like the width of the roadway (Calvert and Snelder, 2018), however, there are rarely any studies that identified the resilience measurement dimensions from construction and management point of view for transportation infrastructures. Moreover, proper distribution and management of assets have an impact on resilience since this ensures the required retrofit, rehabilitation, and capacity expansion of the infrastructures which makes the infrastructures more resilient (Mostafavi, 2017). Yet, current literature provides rarely any list of indicators that address the impact of investment and funding as well as interactions among stakeholders over the resilience of transportation infrastructures. In 2019, a conceptual framework was developed by Zhang et al. (2019) in the field of evacuation transportation systems utilizing strategies to invest in reducing evacuation time. Pregnolato and Dawson (2018) studied the impact of regional investment bias concerning the flood risk of the railway networks. However, none of these studies identifies resilience measurement indicators from the point-of-view of investment and funding. Based on the above discussion, couple of issues are raised-

i. The lack of a list of a comprehensive resilience measurement dimension for transportation infrastructure, and
ii. Lack of a resilience measurement tool for transportation infrastructure networks.

1.3. Research objective

This study aims to develop a model to measure the resilience characteristics rapidity for transportation infrastructures. This study will also develop a decision-making tool to measure the level of resilience of the transportation infrastructures. To fulfill the aim of this study, following objectives were formulated.

i. Identify the potential resilience measuring dimensions for transportation infrastructures,
ii. Identify the significant dimensions in determining resilience of transportation infrastructures,
iii. Develop a decision-making tool based on the resilience measurement dimensions,
iv. Develop model to identify causal effect of significant dimensions over the rapidity of the resilience measure.

The decision-making tool and subsequent results will assist decision-makers in preventing damages due to disruptive events specially flood and hurricane and will save millions of dollars of taxpayers' money. In addition, the findings of this study enable city and county planners to critically prioritize their investments and expenditures for transportation infrastructures in North Texas.

1.4. Dissertation layout

Chapter 1 is consisted of research background, problem statement, and research objective and purpose of the study. Chapter 2 presents a paper that describes an extensive literature review of the existing research studies related to resilience and resilience in transportation infrastructure research. The results of this paper present a list of potential factors that affect transportation infrastructure resilience. Chapter 3 present a paper that describes the preliminary analysis of the collected data. The results of this paper present the significant variables that affect the resilience of the transportation infrastructure resilience. Chapter 4 presents a paper that describes the development of a decision-making tool to comparatively measure the resilience of the transportation infrastructures. Chapter 5 describes a paper that shows the development of models to understand the causal impact of resilience measurement dimensions with the rapidity of the infrastructure. The last chapter (Chapter 6) covers the conclusion, limitation, recommendation, and future work for the study.

CHAPTER 2

DIMENSIONS OF RESILIENCE QUANTIFICATION AND MEASUREMENT IN CRITICAL ROADWAY TRANSPORTATION INFRASTRUCTURE NETWORKS: STATE OF THE ART REVIEW

This chapter will be submitted as:

Nipa, T. J., & Kermanshachi, S. (2021). Dimensions of Resilience Quantification and Measurement in Critical Roadway Transportation Infrastructure Networks: State of the Art Review.

2.1. Abstract

Incorporating resilience in transportation infrastructure planning and analysis has multiple benefits with the vision of having infrastructure with enhanced capability to withstand disruption and to gain rapid recovery. To incorporate resilience, one must know how to quantify resilience which will require a definite list of resilience measuring dimensions. Dimensions that are offered by current literature are not consistent throughout the literature and they do not evaluate the performance of transportation infrastructure. Therefore, this study aims to develop a comprehensive list of dimensions to measure the resilience of the physical segment of the transportation infrastructures. To fulfill this aim, 600 articles were collected from current literature and after initial scrutinization 372 articles were short-listed for systematic content analysis. A list of twenty dimensions to measure the resilience of the transportation infrastructures was developed. Findings showed that the number of intersections in a network is a measure of resilience as disrupted intersections will have a more negative impact on the commute compared to the disrupted roadway; hence, having a greater number of intersections in a network increases the

possibility of more delay which reduces the resilience of the highway network. Another measure of resilience is investment type since traditional investment focusing solely on reducing delay will make the network stronger under mild stress but vulnerable under extreme events. The findings of this study will help researchers to develop quantitative models measuring the resilience of transportation infrastructures and practitioners to prioritize their investment with focus on the vulnerable segments of the transportation networks.

Keywords: Transportation infrastructure resilience, resilience measuring dimensions, critical transportation infrastructure, natural disasters

2.2. Introduction

A phenomenon can be called disaster when it hits an area populated by the human civilization and cause overwhelming damages to the local resources thus diminishes the capacity of the community as well as the community people to recover (Goidal et al., 2019; Westen, 2000). Global warming and climate change are causing natural disasters to be even more destructive as well as more frequent than before (Hu et al., 2018; Djalante et al., 2013; Pamidimukkala et al., 2020b; Rouhanizadeh and Kermanshachi, 2019b). Moreover, the unexpected nature of disaster increases the level of destruction to the critical infrastructure and the collateral damage of the society (Liao et al., 2018). For example, Japan suffered from an earthquake in Kobe district in 1995 which not only cause widespread disruption in the energy sector including electricity, telecommunication, water, and gas, but also caused the closure of commuter rail facilities, and road and port infrastructures for months (Mojtahedi et al., 2017). New York and New Jersey suffered from Hurricane Sandy in 2012 which caused over $70 billion worth of economic loss (Sun et al., 2020). Hurricane Harvey brought the flood in the region of Texas and Louisiana which resulted in devastation worth more than $190 billion (Sun et al., 2020). Texas and Louisiana region suffered from devastating Hurricane Harvey in 2017 which resulted in $190 billion worth of loss by flood in the region (Sun et al., 2020). Not only natural disasters but also manmade disasters are increasing due to uncontrollable technological advancement, economic development, and incompetency of humans and causing unimaginable destructions (Kaur et al., 2019; Pamidimukkala et al., 2021). Ukraine is suffering for more than 20 years from the Chernobyl nuclear power plant accident which happened in 1986 (Kaur et al., 2019). Attack on the world trade center in 2001 caused 2977 fatalities as well as $10 billion worth of infrastructure and property damage (Morgan, 2009).

Interconnectivity and interdependency of critical infrastructures (CIs) make them vulnerable to natural and manmade disasters as destruction in one infrastructure can propagate to the whole system of the built environment (Mojtahedi et al., 2017; Miklasen et al., 2020). Proper functioning of the built environment highly determines the level of wellbeing of the society. For example, a society is dependent on its transportation network system not only for mobility but also for its economic activities (Zhou et al., 2019). Hence, the prosperity and growth of the community highly depend on the functioning network of roads, railways, bridges, etc. (Das, 2020). Alone in the United States of America (USA), the transportation system consists of a complex network of 4 million miles of roads, 600,000 bridges, 19,000 airports, and 3,000 transit providers (Sun et al., 2020). Current advancement of technology and fast globalization making this CI even more complex with many unpredictable nodes of failure (Wan et al., 2018; Kermanshachi et al., 2020a). Transportation systems can be divided into physical, control, surveillance, and communication segments. These segments consist of road networks, at intersections of security, and through a wired or wireless medium. Das (2020) found that the physical segment of the transportation system which consists of roads, bridges, etc. is the costliest and most vulnerable segment among all to extreme events as it is oftentimes operated with its maximum capacity. Damages due to the disaster of the transportation system incur the direct cost of the reconstruction, as well as the indirect cost of downtime as many of the normal economic activities of the affected area, cannot properly operate without a functioning transportation system (Zhang et al., 2017; Safapour and Kermanshachi, 2020). Moreover, recovery of a community also depends on the recovery of the transportation system as damaged transportation network might disconnect the affected community from the rest of the world, thus making it difficult to conduct post-disaster emergency response activities like delivering disaster relief and evacuating affected people, and recovery activities (Zhou et al., 2019; Titko et al., 2020; Safapour et al., 2020a; Safapour and Kermanshachi, 2021b). Hamper of transportation network also creates chaos in the society as it is impossible to continue the operational activities performed by the armed forces of a community (Titko et al., 2020). However, the amount of devastation suffered by a community will not depend on a disaster; hence, disasters with the same intensity and strength will affect a community based on the level of vulnerability and resilience of the community (Lam et al., 2018).

Due to such catastrophic impact of disaster and dependency of community on CIs, modern researchers and policymakers are focusing more on resilience. Around 1973, researcher Holling introduced the concept of resilience in the field of ecology (Sun et al., 2020; Holling, 1973). Since then, the concept of resilience is being studied extensively with respect to many sectors including socio-ecological, community, design, economy, engineering, health, etc. (Mojtahedi et al., 2017). The benefit of a resilient infrastructure system attracted not only the academic community but also different national and state agencies to invest time and resources in the research of resilience. For example, the Department of Homeland Security (DHS) is conducting a program focusing on resilience CIs for more than a decade (Vugrin et al., 2011). The main objective of this program is to guide and inspire agencies to monitor the resilience of the respective infrastructure to assess the potential risk and to reduce the probability of the corresponding damages (Faturechi and Miller-Hooks, 2014). However, researchers only started to significantly incorporate resilience in transportation infrastructure research from 2009 (Wan et al., 2018; Titko et al., 2020).

Incorporating resilience in transportation infrastructure analysis has multiple benefits with the aim of having infrastructure with improved capability to withstand disruption and to gain rapid recovery (Merchman et al., 2020). For example, resilience analysis identifies risks in the system and improves the functionality of the infrastructure in case of natural and/or manmade extreme events. Similarly, it also enhances system safety and helps in optimizing investments (Sun et al., 2020). It is well established the importance of having a resilient transportation infrastructure system for the prosperity of the modern community; however, a well-understood comprehensive model to measure the level of resilience of transportation infrastructure is yet to be developed (Liao et al., 2018). Moreover, dimensions that are offered by the current literature to measure the resilience of the transportation infrastructure systems are not consistent throughout the literature and they are also not enough to interpret the performance of the infrastructures (Liu and McNeil, 2020).

Therefore, this study aims to develop a list of dimensions to measure the level of resilience of the physical segment of the transportation infrastructure. To fulfill the aim of this study following objectives were formulated: (i) determine the existing definitions of resilience adopted in different disciplines, (ii) identify the resilience measurement and quantification dimensions, (iii) evaluate the identified resilience dimensions in determining the physical resilience of transportation infrastructures, and (iv) develop a comprehensive list of dimensions to measure the physical resilience of transportation infrastructure network. The findings of this study will guide practitioners to prioritize their investment with a focus on the vulnerable segments of the transportation networks and adopt appropriate strategies to increase the resilience of the network.

2.3. Method

To successfully achieve the objectives of this study, a multi-step methodology was developed and adopted which is shown in Figure 2-1.

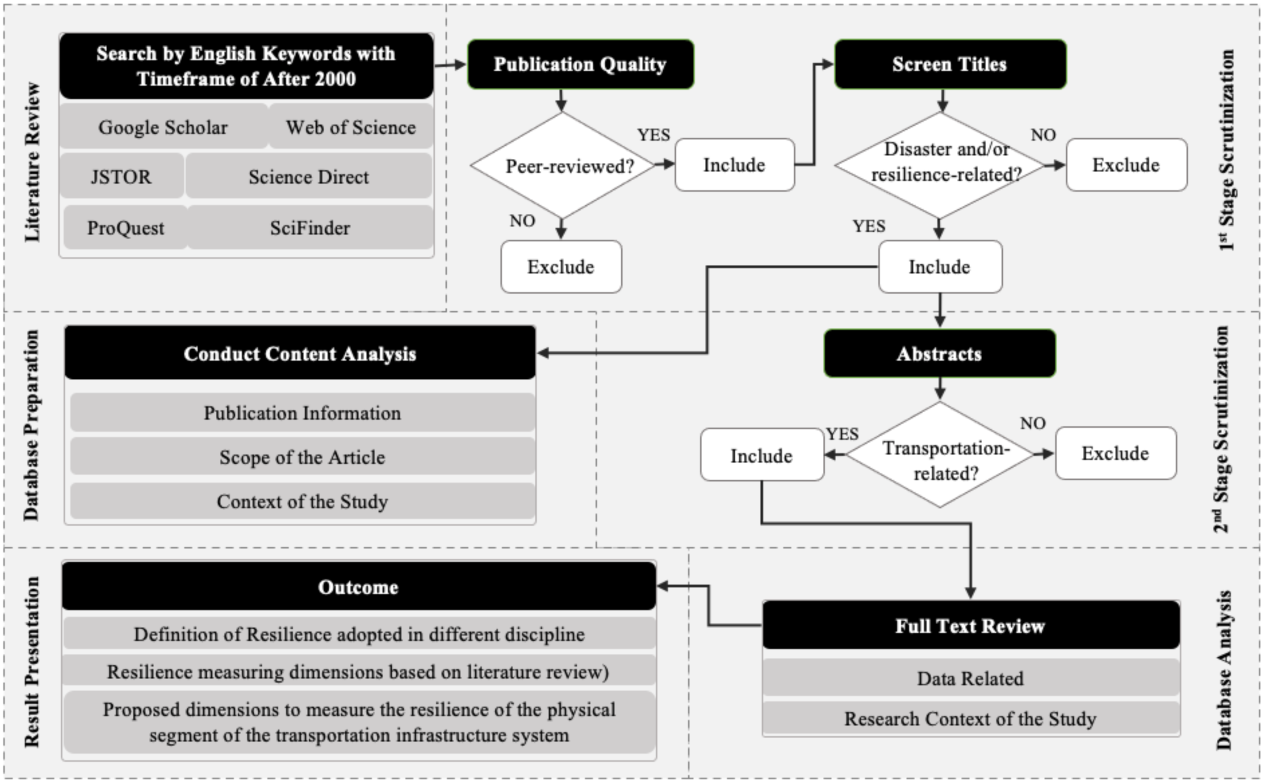


Figure 2-1 Research Methodology

Related academic and reliable resources including journal papers, conference proceedings, dissertations and theses, and research reports were collected. The articles were collected through keywords search method using search engines like Google Scholar, Web of Science, JSTOR, Science Direct, ProQuest, SciFinder. Few example keywords which were used are as following: resilience, resilience system, disaster resilience, resilience indicator, resilience index, resilience measurement, resilience measuring framework, and resilience in the transportation system. Resilience is being analyzed for more than 50 years; however, to be practical and to match the scope of the project, articles published after the year 2000 were focused. Initially 600 articles were collected and based on the study of the abstract, 372 articles were short-listed for systematic content analysis. Content analysis was performed in two stages.

First stage scrutinization- collected articles were scrutinized and necessary information was recorded. During this first stage of scrutinization, the basic information about the articles was collected in a tabular form to prepare a database for the study. Table 2-1 shows the information that was collected during this scrutinization.

Table 2-1 Information collected to prepare the database

Stages	Collected Information
1st Stage Scrutinization	Publication information – - Authors - Affiliation of the Authors - Publication Year - Paper Title - Journal Name - Search Engine - Number of citations Scope of the article – - Discipline - Type of the article - Disaster type - Geographic location Context of the study – - Purpose of the study - Methodology of the study - The outcome of the study - Contribution of the study
2nd Stage Scrutinization	Data related – - Data collection and analysis techniques Research context of the study – - Resilience definition - Resilience measurement dimensions/indicators - Resilience measurement method/frameworks - Other related information

Second stage scrutinization- second stage scrutinization begins with the shortlisting of the studied articles. As one of the objectives of this study is to focus on resilience in transportation infrastructures, related articles were shortlisted before starting the second stage of scrutinization. A total of 109 articles were shortlisted at this point. Each article was studied thoroughly by the authors and necessary information was collected in the database. Table 2-1 shows the information collected during the second stage.

2.4. Overview of the Database

2.4.1. Based on discipline

Collected articles were categorized based on the focused discipline of the study (Figure 2-2). Around 29% (109 counts) of the collected articles were from the discipline of transportation, and the majority of these articles discussed the resilience of transportation networks including roads, bridges, and railway networks, and transportation infrastructures. Several articles from this discipline also focused on asset management, intelligent transportation system, planning and design, and freight transport resilience. 16% (61 counts) of the articles were from the discipline community resilience. Similarly, articles from this category discussed resilience in a community in general or in specific to a certain type of community like urban, rural, city, local, and coastal. 12% (46 counts) of the articles focused on infrastructure resilience.

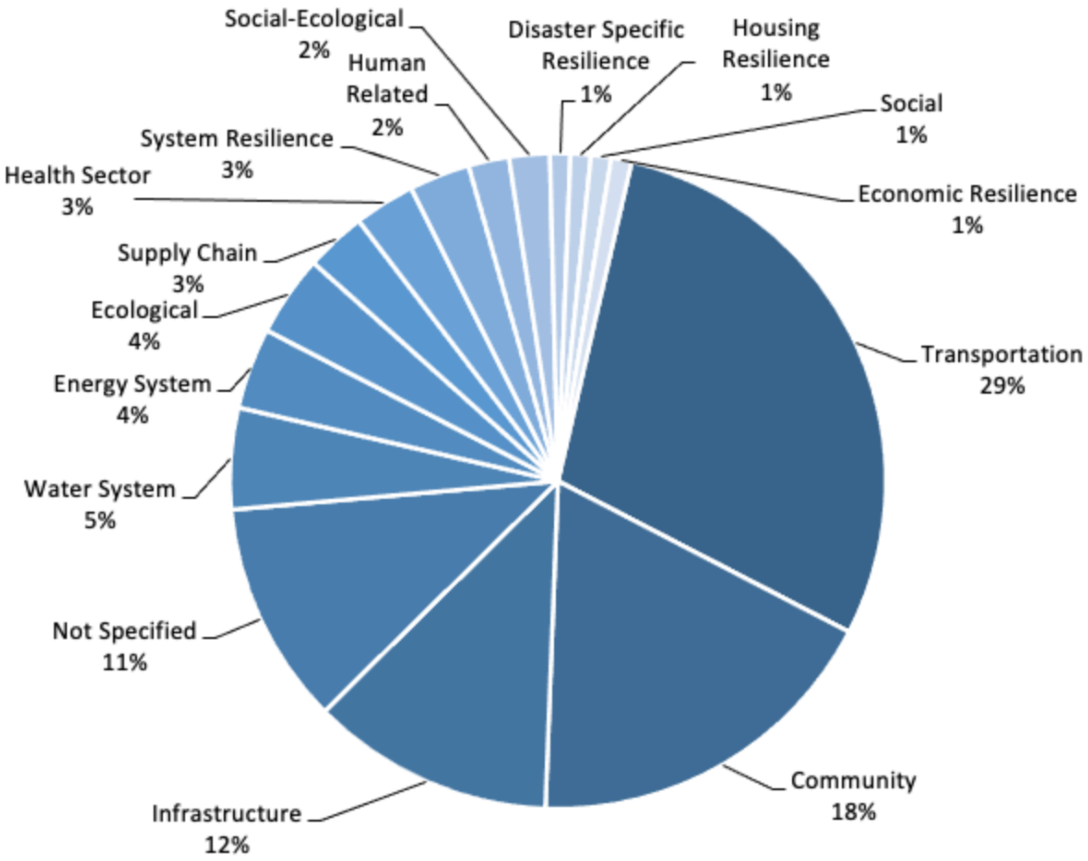


Figure 2-2 Discipline-based resilience studies

2.4.2. Based on number of citations

The number of citations for each article was recorded in the database. Table 2-2 shows the most cited five articles in the database. This table also records the most cited five articles in the discipline of transportation. From this table, it is evident that even though the study of resilience has been done vigorously but the study of resilience in the transportation sector has not been conducted adequately.

Table 2-2 Most cited articles in the area of resilience

#	Article Name	Journal name	Number of Citations	Article Reference
	Five most cited articles of the database			
1	Resilience, adaptability, and transformability in social-ecological systems	Ecology and Society	6760	Walker et al., 2004
2	Social and ecological resilience: are they related?	Progress in Human Geography	5126	Adger, 2000
3	A place-based model for understanding community resilience to natural disasters	Global Environmental Change	3331	Cutter et al., 2008
4	A framework to quantitatively assess and enhance the seismic resilience of communities	Earthquake Spectra	3271	Bruneau et al., 2003
5	Social-ecological Resilience to Coastal Disasters: are they related?	Science	2452	Adger et al., 2005
	Five most cited articles from the discipline of transportation			
1	Generic metrics and quantitative approaches for system resilience as a function of time	Reliability Engineering and System Safety	589	Henry and Ramirez-Marquez, 2012
2	Evacuation transportation modeling: An overview of research, development, and practice	Transportation Research Part C	326	Murray-Tuite and Wolson, 2013
3	Measuring and maximizing resilience of freight transportation networks	Computers and Operations Research	293	Miller-Hooks et al., 2012
4	Resilience: An indicator of recovery capability in intermodal freight transport	Transportation Science	286	Chen and Miller-Hooks, 2012
5	Transportation security and the role of resilience: A foundation for operational metrics	Transport Policy	255	Cox et al., 2011

2.4.3. Based on publication year

Figure 2-3 shows the distribution of the articles based on publication year. The trendline for the distribution of the articles from the transportation discipline confirms that this sector has incorporated resilience in the research mostly from the year 2010. However, the research has speedily gained popularity and the number of published articles in this sector is increasing by the day.

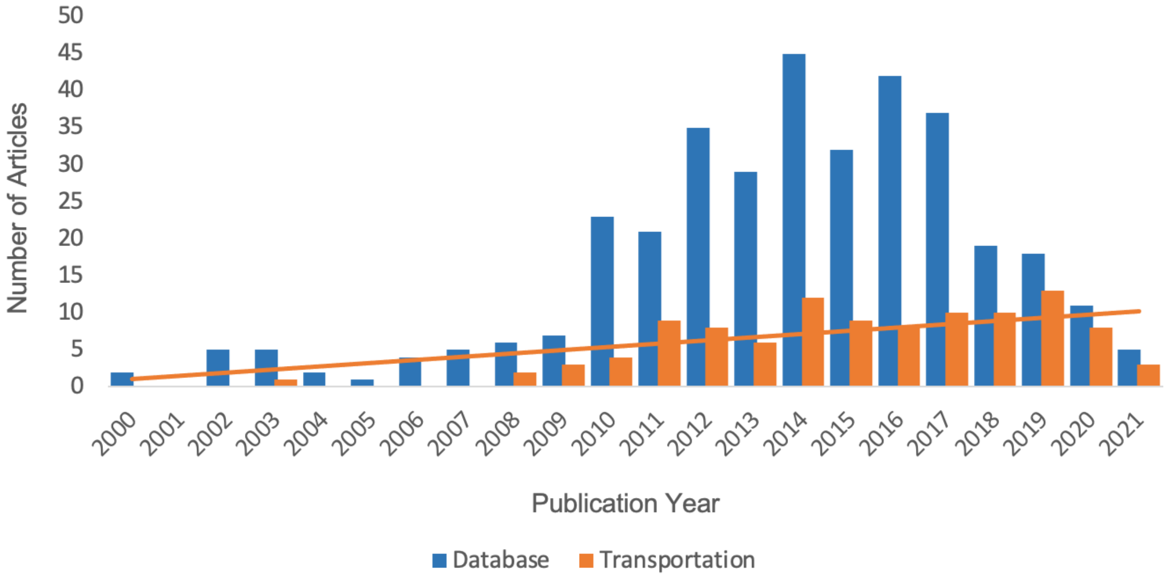


Figure 2-3 Distribution of the articles based on year of publication

2.4.4. Based on publication journal

Table 2-3 shows ten journals with the highest frequency that is the number of articles that are taken from the journal. The journal with the highest frequency is the International Journal of Disaster Risk Reduction. The second highest frequency journal is the Transportation Research Record.

Table 2-3 Frequency of articles by journals

#	Journal Title	Frequency
1	International Journal of Disaster Risk Reduction	18
2	Transportation Research Record: Journal of the Transportation Research Board	11
3	Reliability Engineering and System safety	8
4	Natural Hazards	8
5	Journal of Infrastructure Systems	7
6	Global Environmental Change	6
7	Transportation Research Part A: Policy and Practice	6
8	Journal of Structural Engineering	6
9	Transportation Research Part E: Logistics and Transportation Review	6
10	Risk Analysis	6

2.4.5. Based on disaster type

Figure 2-4 shows the distribution of the articles based on the type of disaster. The majority (22%) of the articles discussed the resilience of transportation infrastructures against natural disasters. The second most discussed topic was disaster in general (20%) without mentioning any specific kinds of events. 15% of the articles mentioned that the article focused on both natural and manmade disasters. 8% of the articles discussed seismic resilience of the transportation infrastructure and 7% of the articles discussed climate change.

Besides, some articles focused on the resilience against a specific type of natural disaster like hurricane, flood, tsunami, and snowfall, and specific type of manmade disaster like terrorism, antagonistic actions, and civil unrest/strike. Few articles focused on technological disasters as well. They included disasters related to the internet and accidents. Some other articles included common or time-dependent events like aging, deteriorating components, and fuel shock.

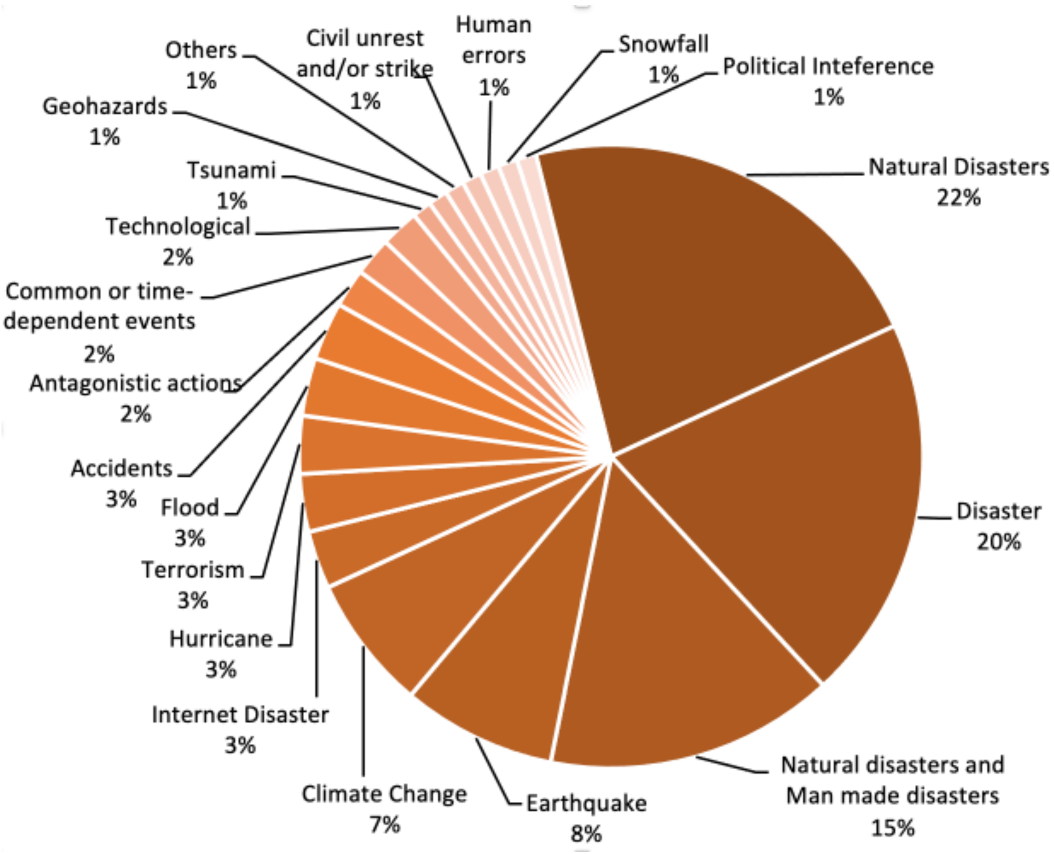


Figure 2-4 Distribution of the articles based on the type of disaster affecting transportation infrastructures

2.4.6. Based on geographical location

Shortlisted articles of the transportation infrastructure were analyzed based on the country of the study. As shown in Figure 2-5, it can be observed that almost half (49%) of the articles discussed transportation infrastructure system resilience in the context of the United States of America (USA). Besides, some articles discussed the resilience of the transportation infrastructure of China, the United Kingdom, France, New Zealand, Sweden, Czech Republic, Singapore, Taiwan, Japan, Nepal, Colombia, Greece, Norway, Ireland, Malaysia, Bangladesh, Hungary, and India.

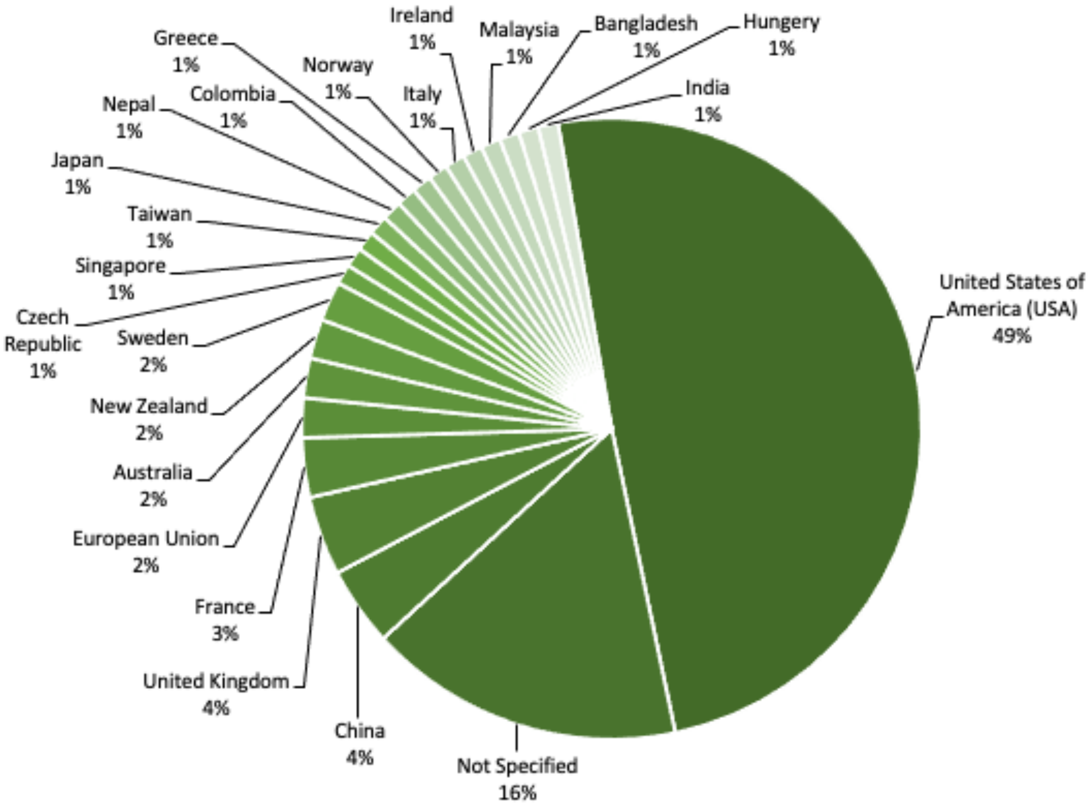


Figure 2-5 Country-based distribution of the publications of resilience in transportation infrastructures

The research team has found that 16% (19 counts) of the articles did not mention any specific geographical location. Such articles were categorized as ‘not specified’ in the geographical location section in the database. However, the study area that is the affiliation of the authors of the articles was noticed to find out the area where the study was conducted. It was found that 16 of the 19 articles were studied in the USA. From Figure 2-6, it is evident that the research of resilience of transportation infrastructure as an independent study is gaining more popularity in the USA compared to other countries.

To understand the importance of the resilience study in different parts of the world, the authors of this study also analyzed the articles based on continents. Figure 2-6 shows that the focus area of 63% of the articles was North America. Europe holds the second-highest value of

19%, Asia holds 12%, Australia and New Zealand hold 5% and South America constitutes only 1% of the articles. Hence, it can be said that developed countries from North America and Europe are focusing more on resilient transportation infrastructures compared to developing and/or under-developed countries from Asia and South America.

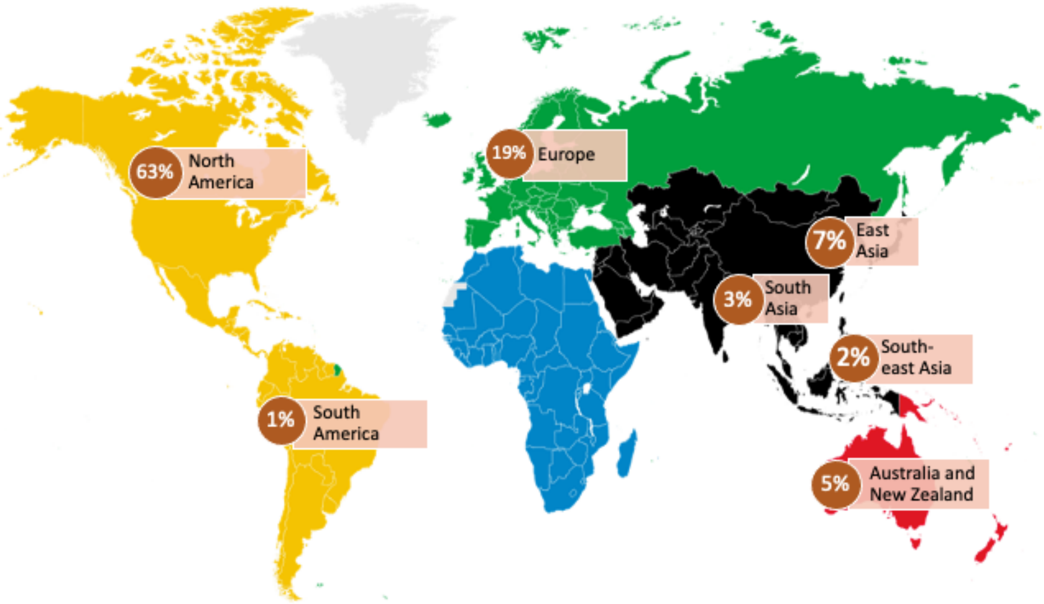


Figure 2-6 Continental distribution of the publication of the transportation discipline

2.5. Results

2.5.1. Definition of resilience

Resilience is a concept that has been explored for more than five decades. With the first conceptualization of resilience by Holling in 1973 in the field of ecology, many other researchers have defined resilience in accordance with their respective fields (Franchin and Cavalieri, 2015; Pamidimukkala et al., 2021). Similarly, different researchers have used different terminologies to define resilience (Nipa et al., 2022b). For example, Sun et al. (2020) have adopted the definition of Bruneau et al., (2003) who used multiple terminologies to define the concept of seismic resilience of the infrastructure in a community (Figure 2-7).

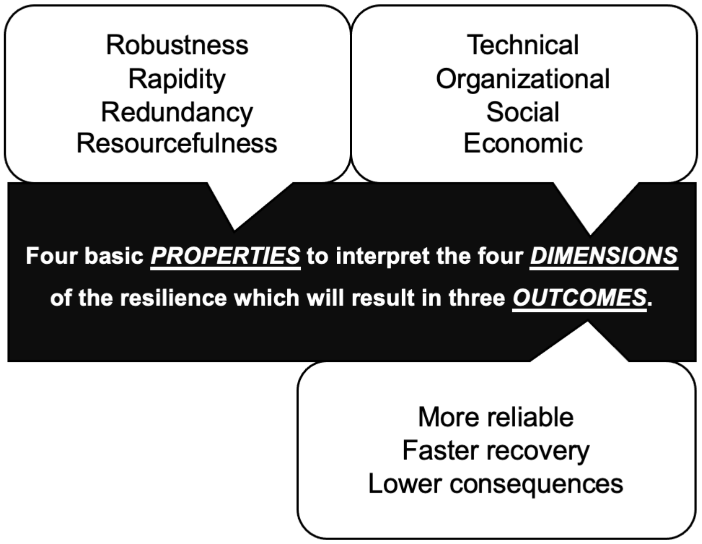


Figure 2-7 Interpretation of resilience definition based on Sun et al. (2020) and Brunue et al. (2003)

On the other hand, Zhang et al. (2017) has defined resilience using only four terminologies while they discussed post-disaster recovery strategies based on resilience for road-bridge networks. These four terminologies are robustness (the ability of the system to provide functionality after being exposed to a disaster), rapidity (speed of recovery), redundancy (number of alternative elements of a system), and resourcefulness (amount of resources to cope with the disaster). McDaniels et al. (2008) used only two terminologies to define the engineering resilience-robustness (level of functional activity of the system after the disaster) and rapidity (time to gain the full functionality of the system after the disaster). The United Nations International Strategy for Disaster Reduction UNISDR (2007) defined resilience with a descriptive nature rather than using definite terminologies. According to UNISDR, resilience is the capacity of the system to maintain functioning on an acceptable level after being exposed to a disastrous event. Such different definitions can be found throughout the literature (Nipa et al., 2022c). Table 2-4 shows different definitions that are being adopted in the different disciplines over the years.

Table 2-4 Definitions of resilience based on different disciplines

Discipline	Definition	Reference
Critical Infrastructure Resilience in Energy Sector	Combination of three purposes- - Applying measures to increase the inherent capability of the system against intentional and unintentional disruptive events. - Establishing alternate activities to reduce the disruption due to such events. - Developing emergency responses to undertake during such events.	Dick et al., 2019
Supply Chain Resilience	Ability to resist, adjust and recuperate from a disaster thus being able to function to meet the demand of the customer.	Hosseini et al., 2019
Community Resilience	Ability to recover from the damage that matches the threat of the disaster.	Lam et al., 2018
Societal Resilience	Resilience is a process to be experienced mainly when a crisis or disaster strikes and describes recovery and transformation into a new state of stability	Fekete, 2018
Ecological Resilience	Refers to the system's capability to bouncing forward to a new equilibrium state after suffering from a disastrous event.	Suarez et al., 2016
Road Network Resilience	Refer to the capability of the system to get the normal activities back after a disaster. This can be confirmed by designing the network with emergency traffic management and evacuation route in case of disaster. Redzuan et al. (2019) used three terminologies to define road network resilience- absorb, adapt and recover.	Redzuan et al., 2019
Housing Resilience	A person’s ability to anticipate the capability of their households to respond to disastrous events.	Jones and Tanner, 2017
Resilience in Health Sector	A health system can be called resilient when it has professionals, institutions, and other related components with- - Ability to respond to the crisis with proper preparation. - Ability to keep working under the disastrous event. - Ability to use the experience if available. - Ability to reorganize if needed.	Kruk et al., 2017

Industrial Resilience	Ability to absorb the impact of the disastrous events to ensure the performance of the system by introducing diversity in the network and firm.	Fraccascia et al., 2017
System Resilience	Seven terminologies were used to define system resilience- ability, adaptability, recovery, rapidity, consistency, performance, and uncertainty. In a nutshell, system resilience refers to the ability of the system to adapt to disturbing events and gain recovery rapidly and in the meantime ensuring consistent performance against uncertain events.	Ayyub et al., 2014
Water Supply Network Resilience	A network that is capable of delivering a predefined demand of water to the consumers at an acceptable level of pressure and quality. Such a network should also be able to restore after a disaster.	Cimellaro et al., 2016
Bridge Resilience	Bridge resilience is having the ability- - Determine the probable level of damage of a bridge under different hazardous events. - Identifying different recovery activities and determining the vulnerability of the affected bridge if the activity is applied.	Gidaris et al., 2017
Freight Transport Resilience	It is the capability of the interconnected logistic network to come back to the normal state of work without disruption after suffering from a disastrous event. This can be attained by ensuring redundant inventory, flexible network, suitable facility location, helpful stakeholders, etc.	Yang et al., 2017
Asset Management Resilience in the Transportation sector	The ability of the decision-makers to choose mitigation options to invest in will reduce the risk for the system.	Herrera et al., 2017
Railway Resilience	Such resilience is defined using terminologies- robustness, resourcefulness, rapid recovery, and adaptability. Tonn et al., (2020) suggested that resilience is a dynamic process that makes the system flexible in shocks which allows the system to have an acceptable level of deviation from the performance.	Tonn et al., 2020
Interorganizational Resilience	Ability to execute a common response to crisis through effective collaboration to reduce the impact of risk.	Therrien et al., 2015
Drainage System Resilience	System's ability to withstand the link failure due to crisis by identifying failure magnitude and duration.	Mugume et al., 2015

Agricultural Resilience	Ability to reduce the impact of disasters through different actions. Examples of such actions are intensification, diversification, alteration, migrations, etc. to implement these activities, resources like natural, human, social, and financial should be available.	Mutabazi et al., 2015
Critical Infrastructure Resilience	Ability to recover in the least amount of time to reach a predefined level of functionality after enduring a minimum level of deviation in performance due to a disaster.	Vugrin et al., 2011
Electricity Sector	Being able to return to sustainable operation with the least disturbances after the known and unknown crisis. A system will be able to have this quality when the system is able to predict, withstand, endure and recuperate from the crisis.	Panteli and Mancarella, 2017; Dick et al., 2019
Resilience in Transportation Sector	The ability of the network to keep working under an unexpected event and using its inherent attributes to minimize the impact and capability to cope with the immediate recovery actions right after the crisis.	Liao et al., 2018; Faturechi and Miller-Hooks., 2014

Even though there exists a vast number of definitions of resilience in the literature based on the sector of study, from Table 2-4 it is evident that the concept of resilience is somewhat similar in all sectors which is bouncing back with minimum performance deviation within the shortest possible time. A system ensures this with its absorptive, adaptive, and restorative capability (Nan and Sansavini, 2017). As recovery phase is a complex phase and recovery time is a fundamental part of the resilience definition, the concept of resilience can be divided into static and dynamic parts interpreting functionality and recovery time respectively (Reggiani, 2013; Rouhanizadeh et al., 2021). Another significant component of resilience is the degree of resilience. Like all CIs, transportation infrastructure is also interconnected with other CIs. This connection puts a threshold in the required level of resilience in one system since one resilient system might make another system vulnerable (Reggiani, 2013).

As resilience is a function of time and performance, a graphical representation of resilience is very effective in understanding the concept of resilience and are of use throughout the literature (Bruneau et al., 2003; Chang and Shinozuka, 2004; Nan and Sansavini, 2017; Fang et al., 2016; Francis and Bekera, 2014). Figure 2-8 shows the concept of resilience concerning different disastrous scenarios and different levels of resilience.

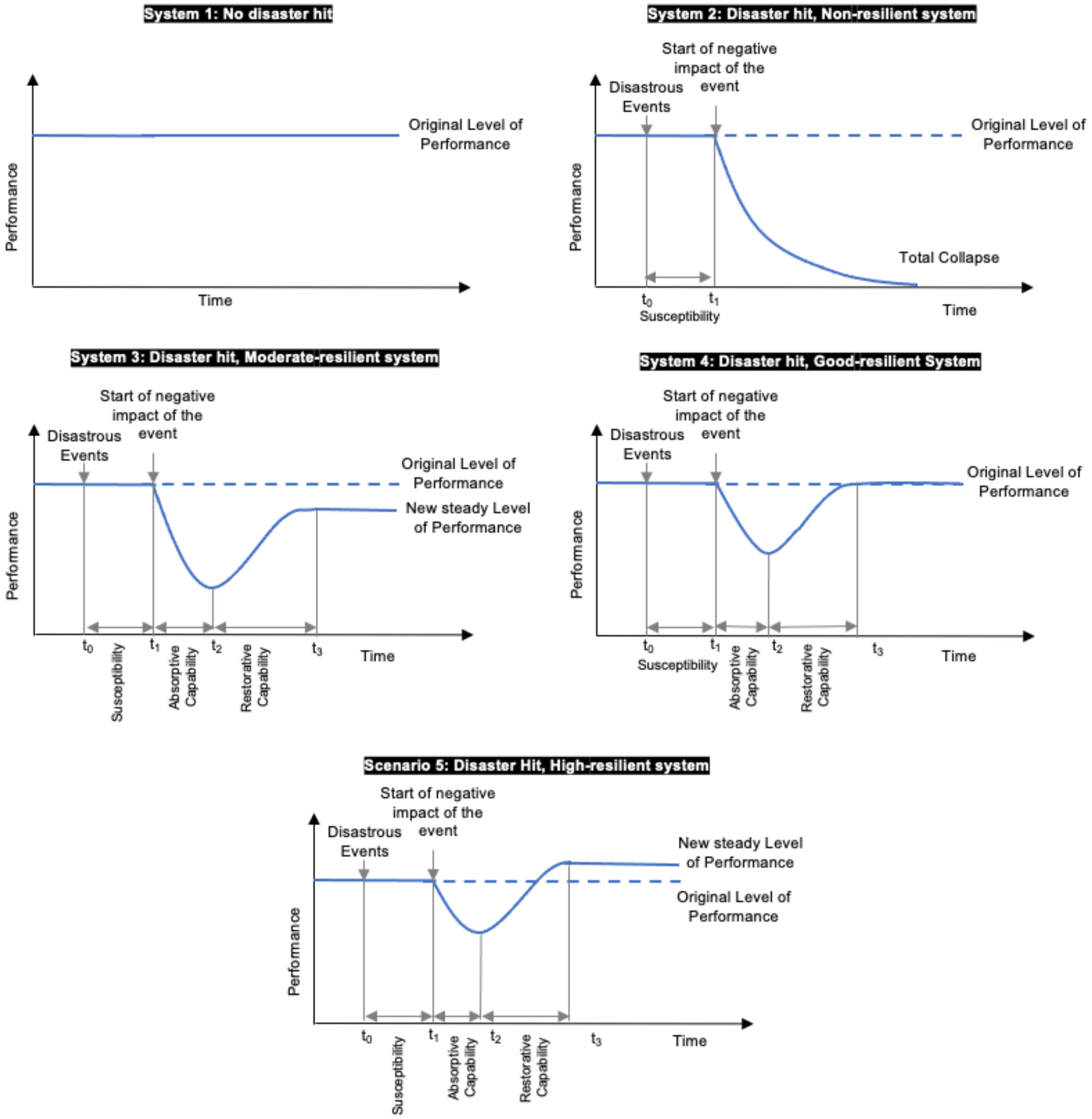


Figure 2-8 Graphical representation of resilience

These graphs are drawn by taking the performance level along Y-axis and time along X-axis. X-axis also mentions few resilience characteristics of the system. When there is no disaster, the system (System 1) performs smoothly over time. When the system with no-resilient capacity gets affected by a disaster, the system will face a total collapse usually (System 2). If the system has a moderate level of resilient capacity, then it will regain some level of performance usually lower than the original after a certain amount of time (System 3). If a system has a good resilient capacity, then it will regain its original level of performance after being affected by a disaster (System 4). Since 2006, researchers and practitioners are considering the reconstruction phase as the opportunity to build the system back better and incorporating this concept with the resilience of the system (Fernandez and Ahmed, 2019; Rouhanizadeh et al., 2019a; Safapour et al., 2020b). In this approach, a system can gain a new steady level of performance that is greater than the original performance level after a disaster (System 5).

2.5.2. Resilience measurement dimensions

Based on the above discussion, it is evident that dimensions that are being used by different sectors vary vastly based on the sector. The most commonly used terminologies among them are robustness, redundancy, resourcefulness, and rapidity (collectively known as 4Rs). Table 2-5 lists a few of the terminologies that are being used to analyze resilience throughout the literature along with their description.

Table 2-5 Terminologies used to define and measure the resilience throughout the literature

#	Term	Description	Frequency
1	Robustness	Having absorptive capability such that the system can withstand a certain level of loss of functionality due to disaster. This is related to the absorptive capability of the system.	15
2	Redundancy	Availability of alternate components so that the system has the ability to face damage without necessarily losing its functionality. This is related to the absorptive capability of the system.	15

3	Resourcefulness	Having emergency material and human resources to gain the fastest recovery after a disaster. This is related to the adaptive capability of the system.	15
4	Rapidity	Rapidity is the time required by the system to restore to the predefined level of performance after a disaster.	15
5	Quality	It is a characteristic of the system that interprets the post-disaster performance of the system.	5
6	Fragility	Fragility indicates the potential level of damage that a system might go through due to a known level of disaster.	5
7	Vulnerability	This is a term which not yet fully understood in the literature. However, it is linked with the exposure of the system to stress. Also, the vulnerability and robustness of a system are inversely proportional to each other.	4
8	Sustainability	The sustainability of a system refers to the tolerance capacity of the system.	4
9	Diversity	Diversity refers to the availability of a wide range of components that will allow the system to withstand multiple threats by providing different functionality.	4
10	Efficiency	The efficiency of a system can be calculated using the ratio between energy supplied to the energy delivered. A system will be called efficient when the value of this ratio is positive.	3
11	Autonomous components	It is the ability of the system to function independently.	3
12	Strength	The capability of the system to withstand the crisis caused by human intent or nature.	3
13	Interdependent	A system with different components should be able to support each other. This ability is known as interdependent in the context of resilience.	3
14	Adaptability	Adaptability can be defined as the quality of the system to learn from previous experience to cope with the upcoming disasters.	5
15	Collaboration	It is the ability of the system or the organization to share information and resources within different components and stakeholders.	5
16	Mobility	It refers to the ability of the network to ensure that the vehicle or people can move from one place to another.	8
17	Safety	It refers to the ability of the system not to put the user at risk of hazardous exposure.	4
18	Resistance	This quality enables a system to withstand the primary impact of a disaster.	3

19	Reliability	It indicates that the characteristics to withstand a wide range of disasters are considered while designing the infrastructure system.	2
20	Response and Recovery	It refers to the combination of resourcefulness and rapidity to regain performance after a disaster.	2
21	Flexibility	It refers to the ability of the system to cope up with a wide range of unforeseen crises.	3
22	Survivability	It is the ability of the system that indicates how much the system can lessen the vulnerability.	3
23	Preparedness	It is an indication of the ability of the system to prepare for a disastrous event beforehand.	10
24	Responsiveness	It is the ability to link the recovery activity with the sudden changes.	5
25	Optimization	Ability to get the best out of a system.	4

However, while discussing the resilience of the transportation infrastructure system, authors found the repetition of 10 terminologies in multiple research articles (Murray-Tuite, 2006; Liao et al., 2018; Moteff, 2012) which are shown in Figure 2-9. Labaka et al. (2016) have linked these terminologies with the four properties of a resilient transportation system. These properties are collectively known as TOSE (technical, organizational, social, and economic resilience).

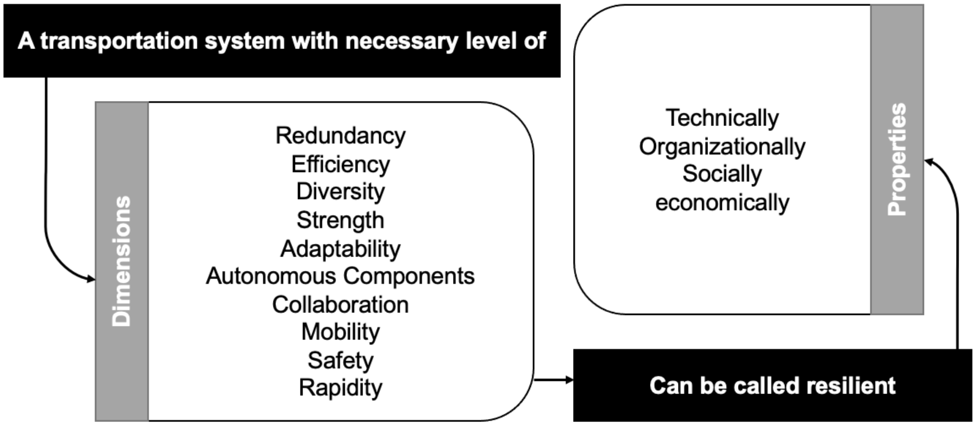


Figure 2-9 Transportation resilience dimensions

Identifying dimensions developed for transportation infrastructure was tiresome as most of the dimensions focus on transportation infrastructure as one of the CIs with interdependency with other CIs. Hence, identified dimensions in the literature are rarely able to fully interpret the resilience of the physical segment of the transportation network like a roadway. For example, Figure 2-9 shows ‘redundancy’ as one of the dimensions to measure transportation resilience. In the transportation sector, one way to achieve redundancy might be having more than the required road for a particular area. However, it is more likely for a disaster to affect a community as a whole and destroying more than one roadway/node of a network. In that case, having emergency reconstruction materials and human resources might be more useful to make the network resilient (Rouhanizadeh et al., 2019b). Therefore, it is necessary to be particular with the dimensions if one wants to use the dimensions in a practical field. Moreover, throughout the literature, the same terminology is defined in multiple ways (Faturechi and Miller-hooks, 2014). This makes it even more essential to prepare a list of dimensions exclusively to measure the physical segment of the transportation infrastructure resilience.

2.6. Proposed dimensions to measure the resilience of transportation infrastructure systems

To quantify the resilience level of the physical infrastructures of the transportation sectors, it is essential to prepare a list of resilience measuring dimensions. The majority of the above-mentioned dimensions are unable to interpret the level of resilience when it comes to the physical properties of the transportation network. Moreover, the majority of these dimensions focus on traffic behavior instead of the characteristics of the road network. Hence, a list of resilience measuring dimensions must be prepared to quantify the resilience of the physical characteristics of the transportation infrastructures. Based on the performed literature review, such a list of resilience dimensions was developed and presented in Table 2-6. A self-explanatory description of each dimension is also included in the table. This description shows how a dimension is linked with the resilience of the roadway network, thus capable of measuring the resilience. For example, the description of the dimension "number of intersections (nodes)" shows that when a roadway network has frequent nodes and if one or multiple nodes gets affected by the disaster, the disruption in traffic mobility will be higher compared to roadway disruption. This is because an ineffective node will hamper the mobility of multiple roadways.

Table 2-6 Proposed Dimensions to measure the resilience of the physical segment of the transportation infrastructure system

#	Dimensions	Description	Reference
1	Number of nodes (intersections)	Ineffective intersection due to disasters will hamper the mobility of the commuter to a greater extent compared to when the roadway gets affected. Therefore, number of intersections within the network highly determines the level of the resilience of a transportation infrastructure network.	Zhang et al., 2017; Ganin et al., 2019
2	Length of the link (roadway without nodes)	Delays caused by roadway disruption are lower compared to delays due to intersection disruption. Hence, a network with a longer roadway length will enhance the resilience of the network.	Ganin et al., 2019
3	The total length of disrupted link	If a long roadway gets affected due to a disaster, it will require a significant number of alternate paths as well as additional time to reroute the vehicles. Hence, the total length of the disturbed link affects the resilience of the link.	Ganin et al., 2019
4	Delay	After a disaster, the road becomes loaded with extra vehicles. Delay is the difference between the travel time required by a traveler to travel the same distance on an empty network and an under-loaded situation.	Ganin et al., 2019
5	Type of investment	If the focus of the capital investment is exclusively on lessening the delay under ordinary functioning conditions, the roadway network becomes indestructible under mild stress. This makes the roadway network defenseless to disastrous events. Hence, the nature of the investment has a relation with the disaster resilience of the infrastructure network.	Ganin et al., 2017; Liao et al., 2018

6	Existence of optional routes	The existence of optional routes increases the redundancy nature of the network. Redundancy of the system has a positive relationship with the resilience of the system.	Safapour and Kermanshachi, 2021c; Sun et al. 2020
7	Access to the resource	A thought-out predefined access route to the resources like supplies, materials, and crew to reestablish the functionality of the affected system will make the system more resilient.	Wan et al., 2018
8	Storing the resource	The safe storage of resources required to reconstruct the affected roadway will have a positive impact on the resilience of the transportation infrastructure network.	Ganin et al., 2017; Wan et al., 2018
9	Previous disaster experience	The management committee with prior experience in managing a transport network under a disastrous event will be more efficient in handling future disasters.	Wan et al., 2018
10	Organizational processes	Different transportation agencies, for example, different Department of Transportations (DOTs), with strong organizational resilience within, will be able to manage the network under a crisis more efficiently.	Liao et al., 2018
11	Information dissemination	To handle disaster properly, prompt decisions have to be made. Transferring information to the right place at the right time is a prerequisite in such situations.	Liao et al., 2018
12	Disaster database	Having a prepared disaster database helps in planning and enforcing disaster prevention plans.	Goidal et al., 2019; Liao et al., 2018
13	Availability of budget	Immediately available budget will significantly help in taking emergency actions required to make the network resilient.	Liao et al., 2018
14	Preparedness actions	To reduce the post-disaster recovery action, corresponding preparedness action must be taken. Preparedness action usually costs much less than corresponding post-disaster recovery action.	Wan et al., 2018; Liao et al., 2018
15	Distance from the epicenter	With the increase in distance from the epicenter of the disaster, the impact of the disaster will lessen.	Li et al., 2016
16	Lane number	When a lane from a particular direction gets affected, one of the lanes from the multiple lanes of opposite direction might work as a temporary lane for the vehicles from the prior direction.	Sun et al., 2020
17	Learning from historical data	Historic data can be traffic-related, passenger related and/or weather-related. These data can be used to estimate link and node disruption probability under a circumstance.	Besinovic, 2020

18	Emergency response equipment	Availability of emergency response equipment will speed up the primary response of the team. For example, if the equipment to remove debris from the roadway is readily available then it will easier for the first responders to start rescue and recovery activities.	Ganin et al., 2017
19	Resource allocation	Allocation of resources also affects the resilience of the transportation infrastructure network.	Liao et al., 2018
20	Emergency Nodes, Normal Nodes	Emergency nodes are the nodes with fire stations, hospitals, etc. Giving extra care while planning and designing such nodes will make increase resilience.	Zhang et al., 2017

2.7. Conclusion

A damaged transportation network hinders the regular commute as well as emergency commute which makes the monetary loss and casualties even greater after a disaster. It is important to make the transportation system resilient so that the affected community stays connected even after suffering from a disaster and can continue the basic function through emergency response and recovery until goes back to normal operation. Researchers and practitioners are searching for ways to integrate the concept of resilience in the transportation infrastructure for almost two decades. The authors found that even though there is a significant study exists in the literature, it is still quite fuzzy when it comes to resilience dimensions to measure transportation resiliency. Therefore, this study aimed to develop a comprehensive list of resilience measuring dimensions for the physical characteristics of the transportation infrastructure. To fulfill the aim of this study, a systematic content analysis of 372 articles including 109 articles on transportation were performed. The findings of this study will significantly help researchers to develop quantitative models measuring the resilience of transportation infrastructures in various regions. The outcomes of this study will also guide practitioners to prioritize their investment with the focus on the vulnerable segments of the transportation networks and adopt effective strategies to increase the resilience of the transportation infrastructures.

CHAPTER 3

RESILIENCE MEASUREMENT IN ROADWAY TRANSPORTATION INFRASTRUCTURES

This chapter will be submitted as:

Nipa, T. J., & Kermanshachi, S. (2021). Resilience Measurement in Roadway Transportation Infrastructures.

3.1. Abstract

Transportation infrastructure resilience is being studied from many perspectives including transportation engineering and traffic engineering, but very rarely from construction engineering. Therefore, this study aims to identify the factors affecting level of resilience of transportation infrastructure from the construction engineering and management point-of-view. This study will also identify the factors of resilience related to investment and funding. To fulfill the purpose of the study, a survey was developed after comprehensive literature review. 92 completed survey responses were collected and analyzed descriptively and quantitatively. Even though around 60% of the participants had more than 20 years of experience each with transportation infrastructure, only 45% were well familiar with the concept of resilience and 73% were involved with the reconstruction projects. Experienced expertise found that having an integrated asset with different ownership in the roadway will increase the time and cost of reconstruction activities hence will reduce the resilience of the structure. Expertise familiar with the concept of resilience agrees that regular funding to resilience enhancement activities will enhance the resilience of infrastructure, however, people not well familiar with the concept of resilience believe that being conservative with the funding is more beneficial compared to investing in the preventive measures that enhance resilience. This difference necessitates educating expertise with concept of resilience. This study identifies factors that are rarely being looked through, hence, can be integrated into the current models/tools to quantify the resilience of the transportation infrastructure. This study will help practitioners on making critical funding and investment decisions as well.

Keywords: Resilience, Transportation engineering, Reconstruction

3.2. Introduction

The network characteristics of the transportation system make it easy prey for unpredictable destructive natural and man-made disasters (Liao et al., 2018). United Sates of America suffers from more than hundred of disasters each year which cause severe damages to critical infrastrucures causing billions of worth of dollars of losses (Patel et al., 2020a). Recovery to the damaged transportation network not only incur the direct cost of rebuilding the infrastructure but also encounter indirect cost occurred due to discontinued social activities (Cox et al., 2011). Moreover, the recovery time of an affected area is positively connected with the functionality of the transportation network, hence, a broken network will slow the recovery of the affected area (Frangopol and Bocchini, 2011). A community has the potential risk of being isolated if the transportation network is broken which will make it difficult for the first responders to render aid to the affected people. An isolated community will have less possibility of getting supplies needed for survival from a relief organization also. Prolonged recovery of the transportation network will make the situation go out of control. Which inspired researchers to look for an innovative way to make the network less prone to hamper due to disaster instead of focusing on recovery (Cutter, 2016). One of the major ways to achieve this is to make the transportation network resilient to natural and man-made disasters.

The concept of resilience was integrated into the field of transportation study only from 2009. However, since then the researchers have progressed the research of resilience in the transportation study very rapidly, hence, current literature provides numerous research articles which defined resilience and developed dimensions, and metrics to measure and quantify the transportation infrastructure resilience. Resilience can be defined as the ability of the system to withstand the adverse impact of the foreseen as well as unforeseen disruptive events to continue functioning at a predefined level (Dick et al., 2019). This ability needs to be quantified before investment can be made to make the system resilient against disasters. Current literature addresses this issue focusing on mainly two characteristics of the transportation system. Firstly, based on network characteristics of the system which mainly focuses on the node-and-link (degree of connectivity) analysis (Ganin et al., 2019). Secondly, based on analysis of traffic which focuses on trip numbers, travel time, traffic flow, etc. (Zhang et al., 2017). The current literature, however, rarely studies resilience from the construction engineering and management point of view. Similarly, even though most of the studies focus on helping make the investment decision for the roadway, they do not discuss the characteristics of investment and funding that help to enhance the resilience of the transportation infrastructure.

Therefore, this study aims to identify the factors that affect the level of resilience of transportation infrastructure from the construction engineering and management point of view. This study will also identify the factors of resilience related to investment and funding. To fulfill the aim of this study, the following objectives were formulated – i. developing a list of potential factors that might affect the resilience of transportation infrastructure, ii. categorizing the factors, and iv. identifying the significant factors from different categories. This study will give specific factors which have an impact on the resilience of the transportation infrastructure, hence, can be used to quantify the resilience of a transportation system.

3.3. Literature review

3.3.1. Concept of resilience

Since the conceptualization by Holling in 1973 (Holling, 1973) in the field of ecology, resilience has been explored for more than five decades. However, many researchers have used the concept of resilience in their respective fields by proposing and adopting a definition more suitable for the field (Franchin and Cavalieri, 2015). Along with the variation of definition in different fields, come vast numbers of terminologies that are being used to define and interpret the concept of resilience. For example, McDaniels et al. (2008) defined engineering resilience using only two terminologies. The first one is robustness which indicates the functionality level of the system after the system has gone through a disruptive event. The second terminology is rapidity which indicates the time required to gain the full functionality after the disaster. However, to define the resilience of road-bridge networks, Zhang et al. (2017) used four terminologies. These terminologies are robustness which indicates the capability to be functional after a disaster, rapidity which indicates the time required to complete the recovery activities, redundancy which indicates the available alternative elements of the system, and resourcefulness which indicates the available resources to perform the recovery activities. Together these four terminologies are known as 4Rs. Many other researchers (Bruneau et al., 2003; Sun et al., 2020) have used 4Rs to explain and define the concept of resilience. Labaka et al. (2016) stated that a system must have four elements to be resilient which are technical, organizational, social, and economic resilience collectively known as TOSE. A system that has the ability to provide sound physical structure to maintain the operation under the crisis is known as technically resilient. A system completed with people who are fit and competent to take the proper and prompt decision under a crisis is known as organizationally resilient. A system that has an educated and prepared neighborhood to get the preliminary help right after a disaster is known as socially resilient. A system with available funding to face and recover from a disaster is known as economically resilient. A system with these four elements will result in a more reliable system that will have lower negative consequences after a disaster and will have faster recovery from a disaster. On the other hand, United Nations International Strategy for Disaster Reduction (UNISDR) adopted a descriptive definition of resilience without focusing on complex terminologies (UNISDR, 2007). They defined resilience as the capability of the system to continue its operation at an acceptable level after being attacked by a disaster.

Reggiani (Reggiani, 2013) found that the definition of resilience can be divided into two parts- static and dynamic. The static part denotes the performance level of the system, and the dynamic part denotes the recovery time. Taking performance as a function of time, the authors illustrated the concept of resilience under different scenarios in Figure 3-1 based on literature (Bruneau et al., 2003; Chang and Shinozuka, 2004; Fang et al., 2016; Francis and Bekera, 2014). Moreover, Fernandez and Ahmed (Fernandez and Ahmed, 2019) found that instead of reconstructing the affected infrastructures into their original capacity, building them better than before is gaining more attention since 2006.

- Scenario #1 – the total collapse of a system with no resilient capacity after a disaster.
- Scenario #2 – performing with a compromised capacity by a system with a moderate level of resiliency after a disaster.
- Scenario #3 – gaining original capacity within a short period of time by a resilient system after a disaster.

- Scenario #4 – functioning with a higher level of capacity than original by incorporating resilience as well as a building-back-better concept after a disaster.

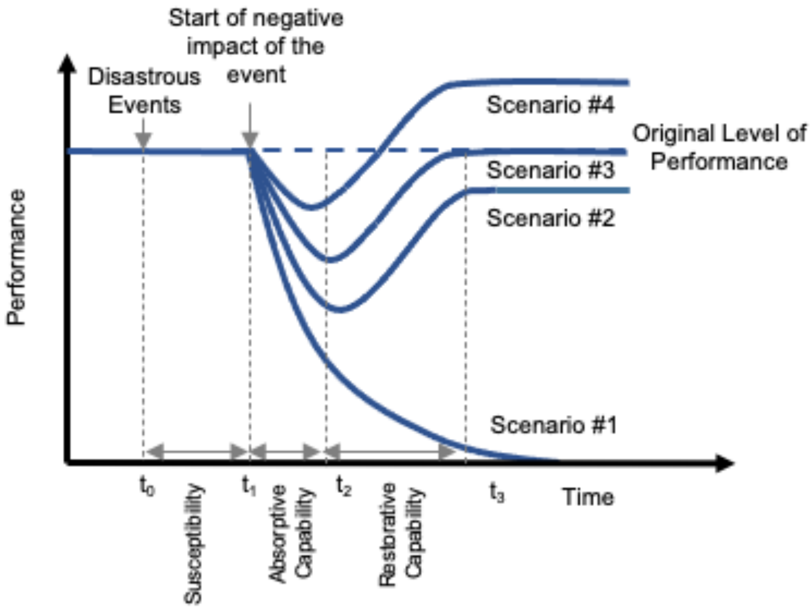


Figure 3-1 Concept of resilience

3.3.2. *Resilience measuring dimensions*

Not only does resilience definition vary based on the discipline but also resilience dimensions. Different researchers from different disciplines used different dimensions to define and measure resilience. For example, to define resilience Nan and Sansavini (2017) focused on three dimensions of a system namely absorptive, adaptive, and restorative capability. Liao et al. (2018) identified four dimensions namely robustness, redundancy, resourcefulness, and rapidity to define the resilience of the transportation infrastructure.

3.3.3. *Transportation resilience*

Though the study of resilience in transportation systems has gained popularity for less than two decades, yet there exists a significant amount of research articles focusing on identifying dimensions to measure resilience in transportation infrastructure. However, while discussing the resilience of the transportation infrastructure system, authors found the repetition of 10 terminologies in multiple research articles (Murray-Tuite, 2006; Moteff, 2012) which are redundancy, efficiency, diversity, strength, adaptability, autonomous components, collaboration, mobility, safety, and rapidity.

3.3.4. Quantitative measures of transportation resilience

Integrating resilience in transportation infrastructure has gained popularity very rapidly and is being studied vigorously, yet, the literature fails to provide a universal resilience measurement tool for transportation infrastructure (Liao et al., 2018). Murray-Tuite (2006) proposed a user equilibrium and system optimum metrics using adaptability, safety, mobility, and recovery as the dimensions to minimize the travel time. Madni and Jackson (2009) proposed a conceptual framework to analyze disruption and provide principles to build a resilient system based on lessons learned. However, this conceptual technique is not exclusive to transportation infrastructure. Using infrastructure type and condition, geographical location, the likelihood of disaster, and disaster type as dimensions, Croope and McNeil (2011) developed a critical infrastructure resilience decision support system (CIR-DSS) to provide cost-benefit alternative strategies to make the recovery and mitigation phase more efficient. This model uses a transportation network system as an example of CIs but is not exclusive to transportation infrastructure systems. Moreover, this model only focuses on the recovery and mitigation phase. Heaslip et al. (2009) proposed a conceptual methodology and Freckelton et al. (2012) expanded the methodology to measure the individual resiliency, community resiliency, economic resiliency, and recovery ability of a transportation network. However, this methodology mainly focuses on the network characteristics of the transportation infrastructure instead of focusing on the physical characteristics of the transportation infrastructure. Assuming equal time intervals in four stages of time of occurrence of the disaster, maximum damage propagation, gradual recovery, and full recovery, a resilience optimization model was proposed by Liao et al. (2018). However, time to reach these four stages might not always be equal.

3.3.5. Challenges of measuring transportation resilience

The above discussion shows that different sectors have different definitions of resilience. Moreover, different researchers from the same sector have proposed different definitions of resilience. Yet, current literature is unable to provide a universal definition of transportation infrastructure resilience, hence, resilience in transportation infrastructure has a lot of definitions throughout the literature (Wan et al., 2018). Moreover, throughout the literature, resilience is being defined with numerous terminologies which creates confusion and makes the word resilience interchangeable with many other terminologies (Tang et al., 2020). Also, the same terminology of resilience is being defined in multiple ways throughout the literature (Faturechi and Miller-Hooks, 2014). This inconsistency makes the existing dimensions to measure the resilience barely enough to interpret the transportation infrastructure resilience which makes quantifying the resilience of transportation even harder (Liu and McNeil, 2020). Hence, current literature is rarely able to provide a tool to quantify transportation resilience (Liao et al., 2018). Moreover, the tools and models which are being used are developed from the transportation engineering point of view and in need of integrating the factors addressed from the construction engineering and management point of view.

3.4. Identification and categorization of elements of transportation infrastructure resilience

After performing a comprehensive review of existing literature regarding resilience in transportation infrastructure, the authors realized that the resilience of transportation needs to be researched from the point of view of construction engineering and management. Keeping that in mind, a list of 37 potential factors that might impact the quantification of transportation infrastructure resilience was prepared (Table 3-1). Identified factors were categorized into construction and structural, management, management personnel, and funding and investment.

Table 3-1 Categorized elements of the transportation infrastructure resilience

Category	#	Variables
Construction and Structural	1	Number of nodes
	2	Length of the link
	3	The total length of the disrupted roadway
	4	Number of lanes
	5	Number of optional routes
	6	Emergency nodes
	7	Having a railroad crossing
	8	The remoteness of the project
	9	Distance of the link/node from the affected area
	10	Shortage of human resource
	11	Shortage of material resources
	12	Availability of emergency response equipment
	13	Storing the resources
	14	Access to emergency resources
Management	15	Rerouting from a node is difficult than rerouting from a link
	16	Ownership of integrated infrastructure assets
	17	time to start reconstruction works
	18	Information dissemination
	19	Maintenance planning includes resilience consideration
	20	Periodical review system for emergency resources
	21	Importance of previous disaster data for the roadway

	22	Access to previous disaster data for the roadway
	23	Database of historical resilience enhancement activities and their associated costs.
Management Personnel	24	Familiarity with the concept of resilience
	25	Involvement in the reconstruction projects
	26	Resilience and efficiency are not correlated
	27	Previous disaster experience
	28	Informed project manager about emergency resources
	29	Level of damage
	30	Company quantifies resilience
Funding and Investment	31	Availability of funding
	32	Time of allocation of funding
	33	Regular funding to resilience enhancement activities
	34	Considering resilience as part of the investment decision-making process
	35	Involvement in the investment decision-making process
	36	Resilience investment only with new projects
	37	Investing in resilience enhancing activities

3.5. Research methodology

Four-step methodology was adopted to perform this study (Figure 3-2). The literature review was the first step where more than 300 hundred articles were studied among which around 100 articles were related to transportation infrastructure resilience. The purpose of this step was to understand the current literature regarding the resilience of transportation infrastructure. At the end of this step, a list of potential factors that might be used to measure and quantify the resilience of transportation infrastructure was prepared. Data collection was the second step where the research team developed a survey based on the prepared list of factors from the first step. Proper approval was collected from Institutional Review Board (IRB) for the survey and distributed among the expertise. The third step consisted of analysis. Both descriptive and quantitative analyses were performed. In the end, the outcome of the analysis was interpreted and explained.

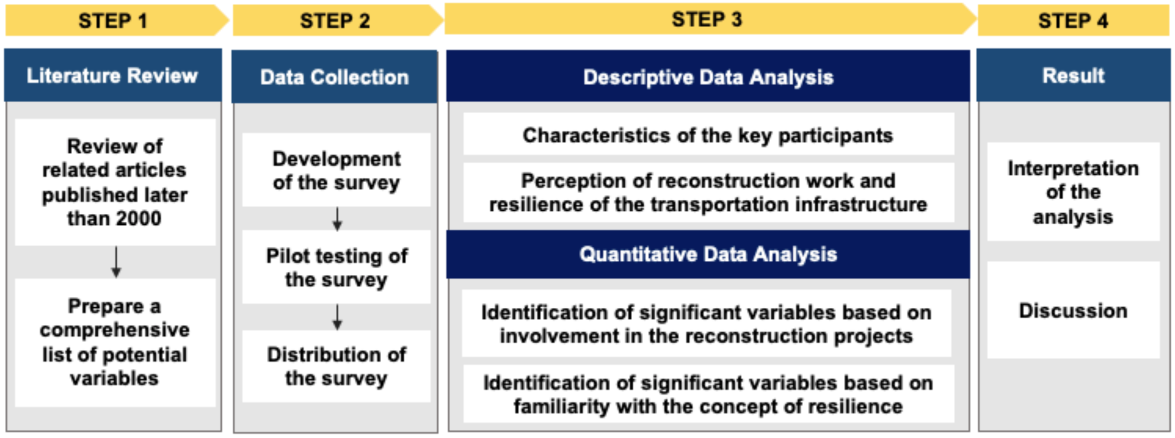


Figure 3-2 Research methodology

3.5.1. Study scope

The massive number of works in the literature regarding transportation infrastructure can be divided into two categories. Articles from the first category discuss the resilience of critical infrastructure (CI). Transportation infrastructure is one of the major CIs, hence, the majority of the studies also included transportation as well as power system, drainage system, health system, etc. These studies focus on interconnectivity and interdependency among critical infrastructures. Articles from the second category portray the resilience of transportation infrastructure from the traffic engineering point of view. Models and tools developed in these articles take traffic-related characteristics like travel time, mode of travel, vehicle number, etc. as dimensions. However, the authors selected the study scope very cautiously for this research report. This research mainly intended to analyze resilience from structural and construction engineering and management point of view for transportation infrastructures. Keeping that in mind, based on literature review and authors' understanding a research framework is designed and followed for this study.

3.5.2. ***Survey administration***

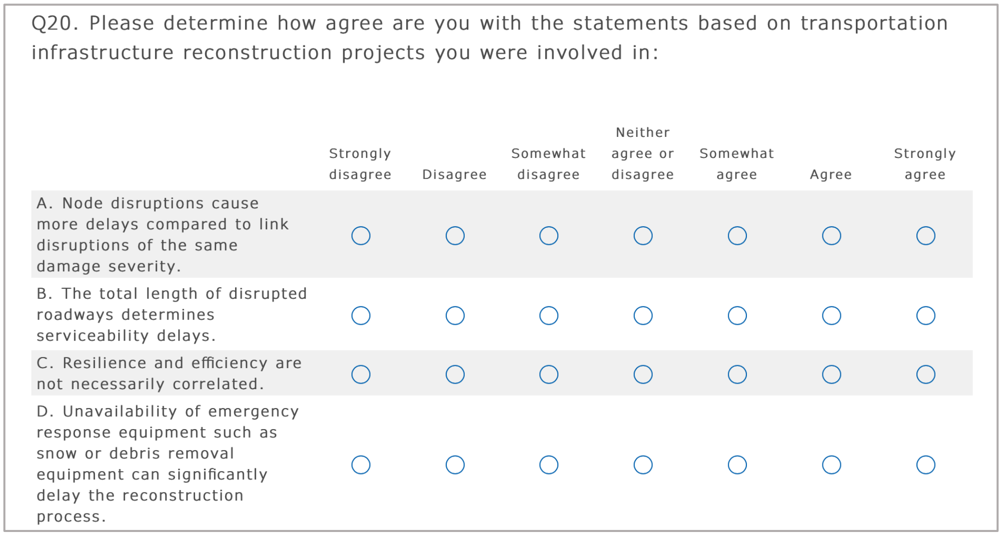
3.5.2.1. Survey development

Related academic resources including journal articles, conference proceedings, dissertations and theses, and research reports were collected. The articles were collected through keywords search method using search engines like Google Scholar, Web of Science, JSTOR, Science Direct, ProQuest, SciFinder. The few example keywords which were used are as follows: resilience, resilience system, disaster resilience, resilience index, resilience measuring framework, and resilience in the transportation system, etc. Resilience is being analyzed for more than 50 years; however, to match the scope of the project, articles published after the year 2000 were focused on. Initially, 600 articles were collected, and based on the study of the abstract, more than 300 articles were short-listed for systematic content analysis. Content analysis was performed in two stages.

First stage scrutinization- collected articles were scrutinized and necessary information was recorded. During this first stage of scrutinization, the basic information about the articles was collected in a tabular form to prepare a database for the study.

Second stage scrutinization- second stage scrutinization begins with the shortlisting of the studied articles. As one of the objectives of this study is to focus on resilience in transportation infrastructures, related articles were shortlisted before starting the second stage of scrutinization. Around 100 articles were shortlisted at this point. Each article was studied thoroughly by the authors and necessary information was collected in the database.

Based on the collected information and authors' understanding, a list of 37 potential dimensions to measure the resilience of the transportation structures is prepared. A structured survey based on each dimension was developed. Each dimension was turned into a question of the survey and the survey consisted of 43 questions including demographic questions. A sample of the survey is presented in Figure 3-3. The developed survey was pilot tested and approval by IRB before distribution.



Q20. Please determine how agree are you with the statements based on transportation infrastructure reconstruction projects you were involved in:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
A. Node disruptions cause more delays compared to link disruptions of the same damage severity.	○	○	○	○	○	○	○
B. The total length of disrupted roadways determines serviceability delays.	○	○	○	○	○	○	○
C. Resilience and efficiency are not necessarily correlated.	○	○	○	○	○	○	○
D. Unavailability of emergency response equipment such as snow or debris removal equipment can significantly delay the reconstruction process.	○	○	○	○	○	○	○

Figure 3-3 Sample from the survey.

3.5.2.2. *Affiliated volunteer responders as study participants*

A list of 500 potential respondents was prepared mentioning their name and contact information. To fulfill the aim of this project experts' opinions were required, hence, the project provided priority to policymakers, project managers, design, and construction engineers, NCTCOG team members, DOT engineers, directors, and their assistants, city engineers, FEMA personnel, etc. as potential participants.

3.5.2.3. *Survey distribution and collection*

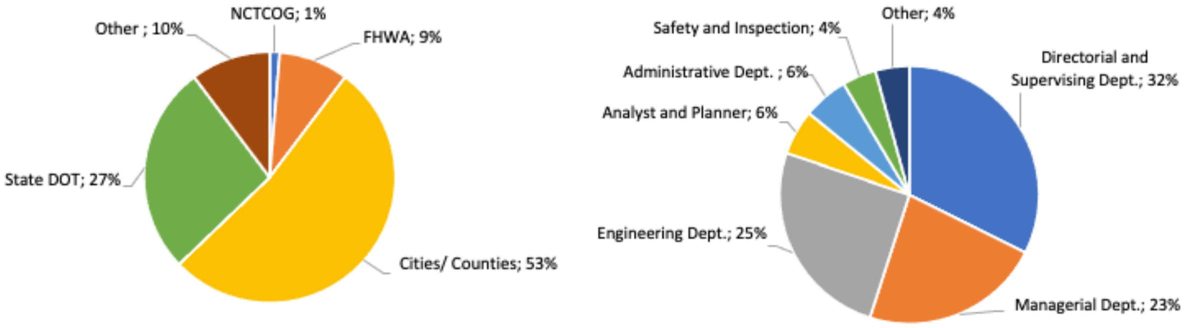
The research team contacted the potential respondents through electronic media. An invitation letter was sent to each potential respondent through email. The letter explained how to participate in the survey and mentioned that the participation is voluntary and will not provide any compensation. After a couple of reminder emails, 92 completed surveys were received.

3.6. Descriptive analysis

3.6.1. Characteristics of the key respondents

3.6.1.1. Based on organization and company

Survey also included demographic questions so that the characteristics of the participants can be analyzed to better understand the responses. Figure 3-4 shows the distribution of the participants based on the organization (Figure 3-4a) and based on the role of the participants in the company (Figure 3-4b).



(a) Distribution of the participants based on the organization

(b) Distribution of the participants based on the role in the company

Figure 3-4 Distribution of the participants based on organization and company

3.6.1.2. Based on the year of experience

Table 3-2 shows the year of experience for the participants. The majority of the participants (60%) have worked in the field of transportation for more than 20 years each.

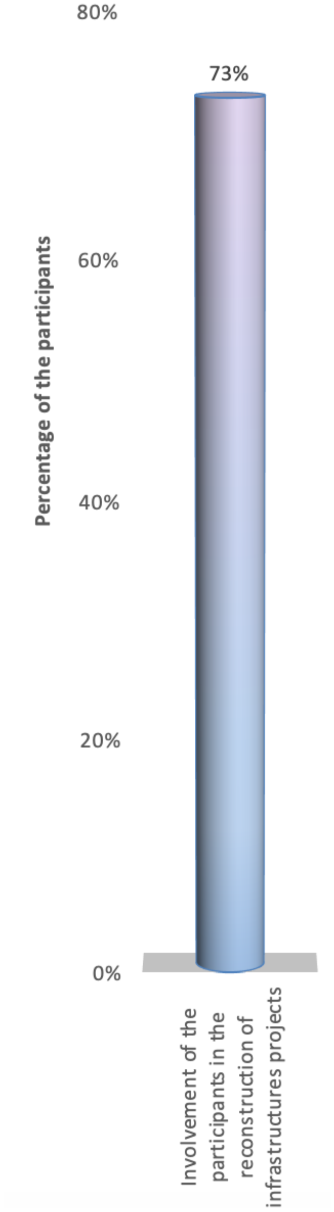
Table 3-2 Year of experience of the participants

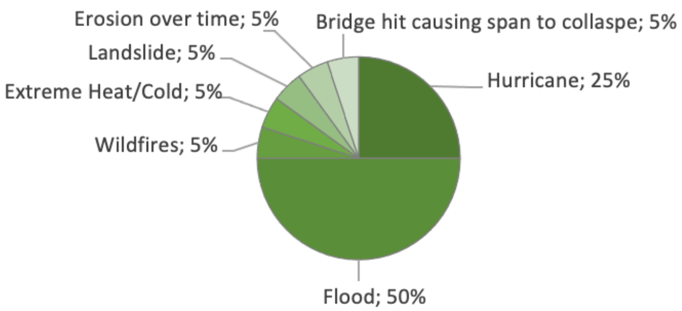
Year of experience	Percentage (%)
Less than 5 years	1%
Between 5 and 10 years	19%
Between 10 and 15 years	11%
Between 16 and 20 years	9%
Between 20 and 25 years	19%
More than 25 years	41%

3.6.2. Perception of reconstruction work and resilience of the transportation infrastructures

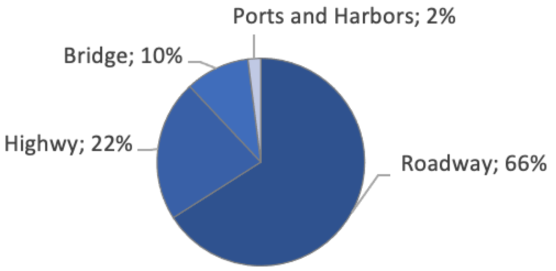
3.6.2.1. Based on the involvement

Figure 3-5 shows that 73% of the participants have been involved in the reconstruction projects at some point in their life. Among them, 50% of the reconstruction project was after the infrastructure was hit by a flood. 25% of the reconstruction projects were conducted because the infrastructure was affected by a hurricane. The rest of the reconstruction work was conducted because the infrastructure was affected by landslides, wildfires, extreme cold/heat weather, etc. Participants have experience in working on small projects as well as big projects. 22% of the participants worked on a project with a budget of less than $1 million whereas 26% of the participants worked on a project with more than $25 million. Similarly, participants of this survey constitute personnel responsible for complex as well as non-complex projects. 45% of the participant worked in non-complex projects whereas 22% of the participants have worked in highly complex projects.

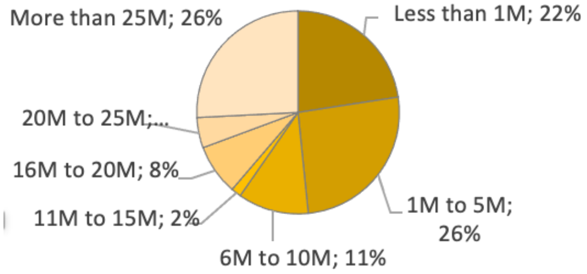




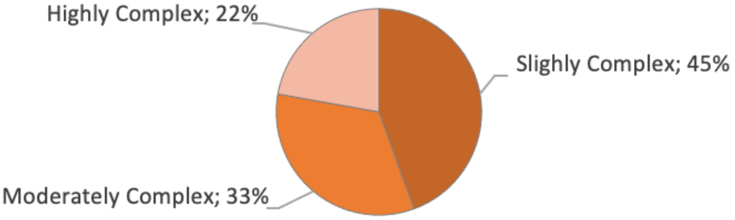
(a) Type of disaster



(b) Type of reconstruction projects



(c) Value of reconstruction projects



(d) Level of complexity

Figure 3-5 Distribution of the participants based on involvement in the reconstruction projects of transportation infrastructures.

3.6.2.2. Based on the perception of the resilience

Survey responses of the participants show that more than 50% of people are unfamiliar or only slightly familiar with the concept of resilience (Figure 3-6). 45% of the participants were well informed about the concept of resilience. This result shows the lack of knowledgeable practitioners regarding the resilience of transportation infrastructure in the field of work.

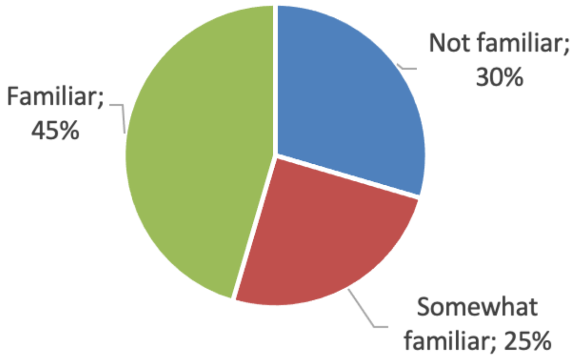
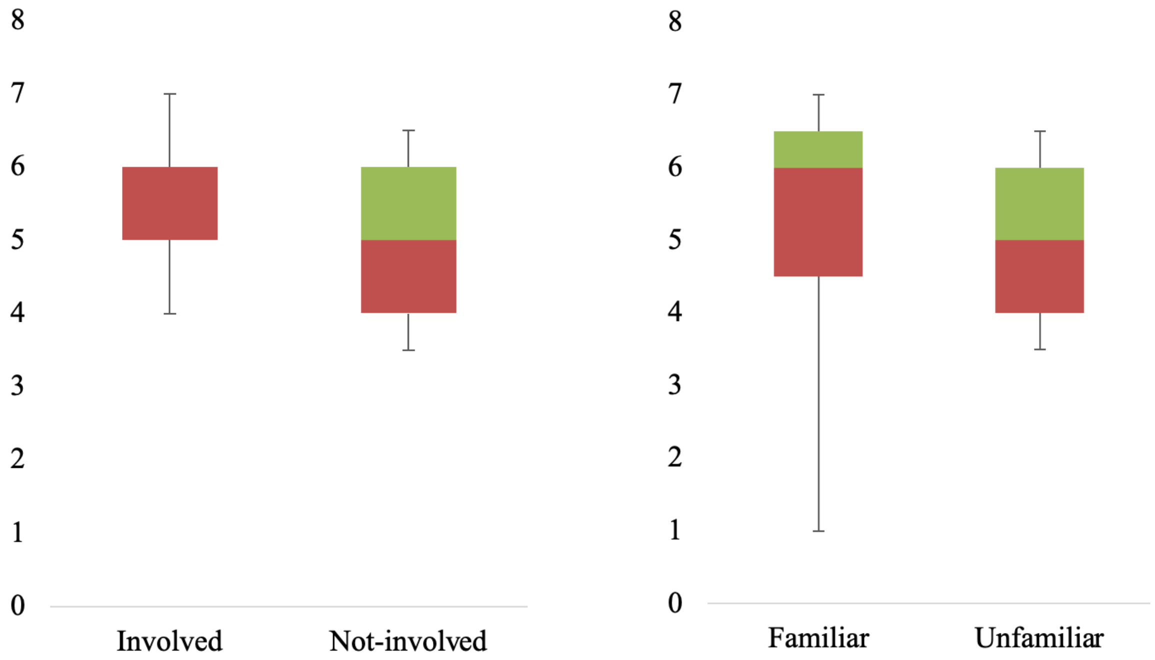


Figure 3-6 Distribution of the participants based on familiarity with the concept of resilience

3.6.2.3. Comparison of means

Figure 3-7a shows the box plots for variables number of optional routes for the criteria involvement. Not only the mean value for the people who were involved in the reconstruction projects are higher but also the whole box appears to be at a higher level compared to the values derived for people who were not involved in the reconstruction projects. A higher value indicates the agreement with the fact that the increased number of optional routes will enhance the resilience of the transportation infrastructure. Figure 3-7b shows the box plots for the variable informed project manager about emergency resources for the criteria familiarity. Box plot drawn for the group familiar is at a higher position as well as the mean value compared to the box plot and mean value for the group unfamiliar. This indicates that the prior group is more inclined to believe that an informed manager about emergency resources will help in making the transportation infrastructure resilient.



(a) Number of optional routes.

(a) Informed project manager about emergency resources

Figure 3-7 Box plots for the data based on (a) involvement in the reconstruction projects and (b) based on familiarity with the concept of resilience

3.7. Statistical analysis

The survey constituted of Likert questions and continuous questions. The authors chose to perform the Kruskal-Wallis test and two-sample t-test to identify the significant variables based on involvement in the reconstruction of transportation infrastructure and based on the familiarity with the concept of resilience. After conducting the test, 21 variables were found to be significant when the grouping condition was involvement in the reconstruction projects and 20 variables were found to be significant when the grouping condition was familiarity with the concept of resilience.

3.8. Interpretation of analysis

In the category of construction and structural, when the division was based on involvement in the reconstruction, the majority (9) of the variables came out to be significant among fourteen variables (Table 3-3). For example, the length of the link has a P-value of 0.055 which indicates that based on the experience in working in reconstruction projects, a bigger length of the link will make the recovery process slow. This can be because rerouting traffic from a longer link will take significantly more time compared to the shorter length of the link. Similarly, the number of optional routes is another significant variable with a P-value of 0.083. Optional routes will facilitate the rerouting more smoothly than when there is a scarcity of optional routes. Hence, the number of optional routes is a measure of resilience. However, when expertise does not have experience in working in the reconstruction project do not necessarily comprehend this difference. That is why the box plot from Figure 3-7a shows that the median value for the group involved is 6 whereas the median value for the group not involved is 5. However, when the division was based on familiarity with the resilience, there were five significant variables among fourteen variables. For example, having a railroad crossing has a p-value of 0.001, this indicates that based on the familiarity with the concept of resilience, while one group find that having a railroad crossing will make the roadway less resilient than not having the railroad crossing, the other group does not necessarily find the existence of a railroad will make the roadway any more or less resilience compared to not having it.

Table 3-3 P-values for variables under the category construction and structural based on involvement in the reconstruction projects and based on familiarity with the concept of resilience respectively

#	Variables	P-Values based on involvement	P-Values based on familiarity
	Construction and Structural		
1	Number of nodes	0.918	0.956
2	Length of the link	0.055*	0.724
3	The total length of the disrupted roadway	0.094*	0.529
4	Number of lanes	0.08*	0.056*
5	Number of optional routes	0.083*	0.848
6	Emergency nodes	0.872	0.638
7	Having a railroad crossing	0.074*	0.001***
8	The remoteness of the project	0.083*	0.956
9	Distance of the link/node from the affected area	0.066*	0.037**
10	Shortage of human resource	0.969	0.057*
11	Shortage of material resources	0.99	0.424
12	Availability of emergency response equipment	0.091*	0.788
13	Storing the resources	0.517	0.005**
14	Access to emergency resources	0.012**	0.69

"*" denotes 90% confidence level, "**" denotes 95% confidence level, "***" denotes 99% confidence level

In the category of management, when the division was based on involvement in the reconstruction projects, five variables were found to be significant among nine variables (Table 3-4). For example, ownership of the integrated infrastructure assets is a significant variable with a P-value of 0.008. When a roadway network has integrated assets (signals, intelligent transportation system apparatus, utility conduits, etc.) with different authorities, recovery works will be delayed if the management from both authorities works together. Hence, having such assets in the network will make the network less resilient. However, professionals with experience in working in reconstruction realize this scenario more compared to professionals without experience in working in reconstruction projects. When the division was based on familiarity with the concept of resilience, six variables were found to be significant among nine variables. For example, the periodical review system for emergency resources is a significant variable with a P-value of 0.077.

Professionals with the knowledge of resilience find it beneficial to arrange periodical review meetings for the emergency resources so that the responsible person does not have to wait for emergency resources when needed right after a disaster. Personnel without proper knowledge of resilience might believe preparing personnel for a might happen event would not be a cost-effective activity.

Table 3-4 P-values for variables under the category management based on criteria involvement and familiarity

#	Variables	P-Values based on involvement	P-Values based on familiarity
	Management		
1	Rerouting from a node is difficult than rerouting from a link	0.746	0.003**
2	Ownership of integrated infrastructure assets	0.008**	0.008**
3	time to start reconstruction works	0.086*	0.005**
4	Information dissemination	0.967	0.627
5	Maintenance planning includes resilience consideration	0.054*	0.037**
6	Periodical review system for emergency resources	0.641	0.077*
7	Importance of previous disaster data for the roadway	0.021**	0.833
8	Access to previous disaster data for the roadway	0.071*	0.094*
9	Database of historical resilience enhancement activities and their associated costs.	0.807	0.871

In the category of management personnel, when the grouping was based on involvement in reconstruction projects, five variables were found to be significant among seven variables (Table 3-5). For example, familiarity with the concept of resilience is a significant variable with a P-value of 0.067. professionals from their experience in reconstruction projects found that it is important for the authority responsible for the structure stays familiar with the concept of resilience to make the structure resilient. When the division was based on familiarity with the concept of resilience, only two variables were found to be significant among the seven variables. For example, informed project manager about emergency resources is a significant variable with a P-value of 0.097. When people are not aware of the concept of resilience, the necessity of having an informed project manager to have a speedy recovery after a disaster is not well understood. This can be validated from Figure 3-7b where the box plot for the data for the variable informed project manager about emergency resources is shown. When the grouping was based on familiarity the box appears higher in place compared to when the grouping was based on unfamiliarity.

Table 3-5 P-values for variables under the category management personnel based on criteria involvement and familiarity

#	Variables	P-Values based on involvement	P-Values based on familiarity
	Management Personnel		
1	Resilience and efficiency are not correlated	0.097*	0.263
2	Previous disaster experience	0.851	0.606
3	Informed project manager about emergency resources	0.966	0.097*
4	Level of damage	0.492	0.706
5	Company quantifies resilience	0.017**	0.024**

In the category of funding and investment, when the division was based on involvement in the reconstruction projects, four variables were found to be significant among seven variables (Table 3-6). For example, time of allocation of funding is a significant variable with a p-value of 0.001. This is because funding focused on reducing immediate traffic delays will make the network stronger under normal conditions and vulnerable under extreme conditions. The impact of this phenomenon has a connection with the experience of working in reconstruction projects. However, when the grouping was based on familiarity with the concept of resilience, all seven variables were found to be significant. This signifies the importance of being familiar with the concept of resilience.

Table 3-6 P-values for variables under the category funding and investment based on criteria involvement and familiarity

#	Variables	P-Values based on involvement	P-Values based on familiarity
	Funding and investment		
1	Availability of funding	0.385	0.001***
2	Time of allocation of funding	0.001***	0.001***
3	Regular funding to resilience enhancement activities	0.001***	0.001***
4	Considering resilience as part of the investment decision-making process	0.391	0.041**
5	Involvement in the investment decision-making process	0.949	0.072*
6	Resilience investment only with new projects	0.012**	0.051*
7	Investing in resilience enhancing activities	0.054*	0.054*

3.9. Discussion

Since the survey was distributed among professionals in the field of transportation engineering working in different state, city, national and international organizations, the majority (73%) of the participants were found to have experience in the transportation reconstruction project after the disaster (Figure 3-7). Also, around 60% of the participants have more than 20 years of experience in working in the field of transportation (Table 3-2). Yet only 45% of the participants were well familiar with the concept of resilience. Table 3-3 shows that not only involvement in the reconstruction project but also familiarity with the concept of resilience is needed to comprehend the significant variables which are needed to measure and quantify the resilience of a transportation network from a construction engineering and management point of view. In addition, to make proper investment and funding decisions, familiarity with the concept of resilience should be a must-have quality.

3.10. Conclusion

With the rapid increase in the number of commuters day by day, the dependency of human civilization on transportation infrastructures is increasing constantly. Not only are commuters get negatively affected by a damaged transportation network, but also a community has the potential to be isolated and suffer from physical as well as a monetary inconvenience by such a transportation network. Researchers and practitioners including different governmental organizations are focusing on making the transportation infrastructure resilient instead of investing solely in recovery activity. This resulted in a significant surge in resilience study in the field of transportation infrastructure. Yet, the literature rarely provides dimensions, models, and/or tools that quantify resilience comprehensively including the perspective of construction engineering and management. Therefore, this study aimed to identify the factors that affect the level of resilience of transportation infrastructure from the construction engineering and management point of view. This study also identified the factors of resilience related to investment and funding. Results indicated that among 37 variables, 21 were found to be significant based on having experience in working in reconstruction projects. For example, the total length of the disrupted roadway was found to be a significant variable. This indicates that when working in the reconstruction projects, expertise found that the length of the disrupted roadway relates to the recovery cost and time of the reconstruction work which makes it a significant variable. However, people without such experience rarely make the connection between the length of the disrupted roadway and the resilience of the transportation infrastructure. Moreover, when the division was based on familiarity with the concept of resilience, all 7 variables from the category funding and investment are found to be significant. This shows the significance of educating responsible personnel about the concept and integration of the concept of resilience in transportation infrastructures. Significant variables identified in this study can be incorporated into the existing models to have a comprehensive model to quantify transportation infrastructure resilience. Moreover, this study gives specific factors which have an impact on the resilience of the transportation infrastructure, hence, can be used to quantify the resilience of a transportation system. This study will help practitioners how much as well as when to invest in the resilience of the transportation infrastructure.

ACKNOWLEDGMENT

We gratefully acknowledge the support and generosity of the Transportation Consortium of South-Central States (Tran-SET), without which the present study could not have been completed.

CHAPTER 4

DEVELOPMENT OF DECISION-MAKING SYSTEM TO MEASURE THE RESILIENCE LEVEL OF HIGHWAY PROJECTS

This chapter will be submitted as:

Nipa, T. J., & Kermanshachi, S. (2021). Development of Decision-Making System to Measure the Resilience Level of Highway Projects.

4.1. Abstract

The recent increase in frequency and intensity of disasters has made transportation infrastructures vulnerable to disruptions. Loss of functionality of the transportation system will multiply the economic loss by many folds since recovery pace of the community depends on continued functionality of transportation infrastructures. Resilient infrastructure will ensure functionality with minimal discontinuity. Prioritizing critical infrastructure for resilience enhancing investments is a troublesome activity since there exist rarely a tool to compare the resilience level of existing transportation infrastructure especially from the construction and management point of view. Therefore, this study aims to identify significant dimensions to measure the resilience of the transportation infrastructures and utilize the identified dimensions to develop a decision-making tool. A survey supported by a comprehensive literature review was conducted to collect the data. Different statistical tests were performed on the collected data. It was found that network characteristics (length of the link, number of lanes, number of optional routes, etc.), organizational characteristics (time to start reconstruction work, knowledge of the employee, resilience measurement experience, etc.), and information related to data (previous data availability and data accessibility, etc.) have major impacts on the potential resilience of the transportation

infrastructure. Based on the impact of statistically significant indicators, a resilience measurement tool was developed. The indicators were provided with weights to reflect the impact of indicators on the resilience of the transportation infrastructures. The user will be able to choose a score from a scale of "1" through "9" which will be multiplied by the weight of the indicator and the multiplied value will show the resilience impact value for the indicator. Cumulation of the resilience impact values for the indicators will show the level of resilience of the project. The outcome of this study will help decision-makers and practitioners to rank the projects for resilience enhancement activities and provide funding accordingly.

4.2. Introduction

With an ever-growing population, both in the United States and worldwide, the number of consumers of services provided by transportation infrastructure systems is increasing rapidly. To meet the demand of increasing commuters, transportation infrastructures are becoming costly and complex. Destruction of these complex structures due to disastrous events not only causes a direct cost of reconstruction but also incurs an indirect cost by slowing down the regular economic activities of the affected area (Cox et al., 2011; Rouhanizadeh and Kermanshachi, 2021a). Such costs can highly be reduced if the structure is resilient enough to suffer only from the minimal impact of the disaster and have the capability to bounce back to its original level of operation within a short period of time. Moreover, to prioritize the limited funding and to invest in resilience-enhancing activities, it is important to know the level of resilience of the existing infrastructure.

Likewise, the focus of the traditional recovery-based approach is converting into a more resilient-based approach for transportation infrastructures (Cutter, 2016; Brummitt et al., 2012). Researchers as well as national, and international organizations are prioritizing resilience over recovery in recent years (Wan et al., 2018). Hence, the concept of resilience is gaining popularity rapidly and being studied vigorously. Resilience ensures that the system can withstand foreseen and unforeseen disasters with minimum disruption in the functionality (Dick et al., 2019). A system will gain resilient characteristics when resilience enhancement activities are introduced in the system prior to the event of disaster. Resilience enhancement activities will require investment and funding in the roadway. With the limited number of resources available, it is always a great dilemma for the decision-makers to decide on critical projects to choose for restoration and renovation activities (Kong et al., 2019). In this scenario, identification of level of resilience of different transportation infrastructure projects and being able to compare the outcome will help in identifying critical project. However, the concept of resilience is being incorporated in the field of transportation research only since 2009 (Wan et al., 2018). Yet, it gained rapid popularity and there exist a significant number of research regarding resilience in the field of transportation infrastructures. Existing literature is unable to comprehensively measure the level of resilience of the transportation infrastructure due to its complex nature of uncertainty and interconnectivity (Sun et al., 2018). There exist a very limited number of articles that studied resilience of transportation infrastructure from construction and management point of view.

Therefore, this study focused on identifying resilience measurement dimensions of transportation infrastructure and developing a decision-making tool to measure the level of resilience of transportation infrastructure. To fulfill the aim of this study, following objectives were constructed- (i) developing potential list of dimensions, (ii) identifying significant variables, (iii) ranking and weighting of the significant variables, and (iv) development of the tool. Outcome of this study will boost-up decision-makers confidence in selecting critical transportation infrastructure project for funding and investment.

4.3. Literature Review

4.3.1. Concept of Resilience

Since the conceptualization of resilience by Holling in 1973 in the field of ecology, resilience has been researched and explored for more than five decades. Many researchers have used the concept of resilience in their respective fields (Rouhanizadeh and Kermanshachi, 2021b) and proposed definitions that are more suitable for those particular fields (Franchin and Cavalieri, 2015). There are vast numbers of terminologies in different fields which are being used to define and interpret the concept of resilience. For example, McDaniels et al. (2008) defined engineering resilience using only two terminologies. The first one is "robustness" which indicates the level of functionality of the system after the system has gone through a disruptive event. The second is "rapidity" which indicates the time required to gain full functionality after a disaster. However, to define the resilience of road-bridge networks, Zhang et al. (2017) used four terminologies. These are "robustness" (the capability to be functional after a disaster), "rapidity" (the time required to complete the recovery activities), "redundancy" (the availability of the alternative elements of the system to be functional), and "resourcefulness" (the availability of the resources to perform the recovery activities). Together these four terminologies are known as "4Rs". Many other researchers have used 4Rs to explain and define the concept of resilience (Bruneau et al., 2003; Sun et al., 2018). According to Labaka et al. (2016), a system must have four elements to be resilient which are technical, organizational, social, and economic resilience: collectively known as TOSE. A system with the ability to provide sound physical structure to maintain the operation under the crisis is technically resilient. A system composed of people who are fit and competent to take the proper and prompt decision under a crisis is organizationally resilient. A system that has an educated and prepared neighborhood to get the preliminary help right after a disaster is socially resilient. A system with available funding to recover from a disaster is economically resilient. Systems with these four elements will have lower negative consequences after a disaster and faster recovery from a disaster. On the other hand, United Nations International Strategy for Disaster Reduction (UNISDR, 2007) adopted a descriptive definition of resilience without focusing on complex terminologies. They defined resilience as the capability of the system to continue its operation at an acceptable level after being attacked by a disaster. Similarly, there exists a vast number of definitions of resilience throughout the literature.

Moreover, Reggiani (2013) found that the definition of resilience can be divided into two parts: static and dynamic. The static part denotes the performance level of the system, and the dynamic part denotes the recovery time required for the system to gain the pre-defined performance level after a disaster. Taking performance as a function of time, the concept of resilience under different scenarios is illustrated in Figure 4-1.

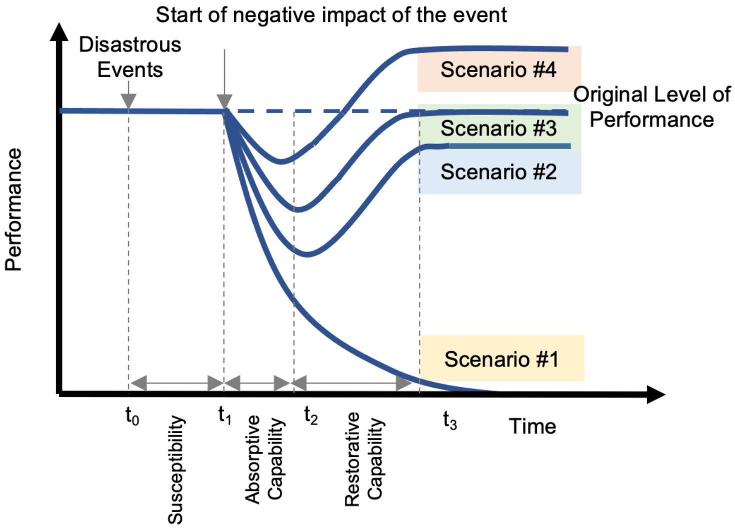


Figure 4-1 Graphical representation of resilience

These graphs are developed by taking the performance level along the Y-axis and time along the X-axis. The X-axis also mentions some resilience characteristics of the system. When the system with no-resilient capacity gets affected by a disaster, the system will face a total collapse (System 1). If the system has a moderate level of resilience, then it will regain some level of performance usually lower than the original capacity, after a certain amount of time (System 2). If a system has solid resilience capacity, then it will regain its original level of performance after being affected by a disaster (System 3). Since 2006, researchers and practitioners are considering the reconstruction phase as the opportunity to build the system back better (Fernandez and Ahmed, 2019). In that case, a system can gain a new steady level of performance that is greater than the original performance level after a disaster (System 4).

4.3.2. Resilience in Transportation Sector

The study of resilience in the transportation sector has gained popularity for nearly two decades (Rouhanizadeh and Kermanshachi, 2020a), yet there exists a significant amount of research articles focusing on identifying dimensions to measure resilience in transportation infrastructure (Rouhanizadeh et al., 2020a). While discussing the resilience of the transportation infrastructure systems, the repetition of ten dimensions in multiple research articles was observed (Murray-Tuite, 2006; Liao et al., 2018; Moteff, 2012) which is shown in Table 4-1.

Table 4-1 Exiting transportation resilience dimensions

#	Term	Definition	Frequency
1	Redundancy	Measure of the absorptive capability of the system.	15
2	Rapidity	Refers to the system's recovery speed and recovery time.	15
3	Mobility	Capability of the system to move people and/or vehicles from one place to another.	8
4	Collaboration	Capability of the system to maintain a healthy sharing system with other organizations or stakeholders.	5
5	Safety	Capability of the system to provide risk-free service to the consumers.	4
6	Diversity	Ability to withstand the loss of functionality due to different kinds of threats.	4
7	Adaptability	Capability of the system to utilize lessons learned.	5
8	Strength	Inherent capability of the system to resist disasters.	3
9	Autonomous Components	Capability of the system to function independently.	3
10	Efficiency	Measure of output energy compared to input energy.	3

4.3.4. Quantification Measures of Resilience in Transportation Infrastructure Systems

Integrating resilience in transportation infrastructure has rapidly gained popularity and is being studied vigorously (Rouhanizadeh and Kermanshachi, 2021c); yet, the literature fails to provide a universal resilience measurement tool for transportation infrastructure (Liao et al., 2018; Nipa et al., 2019). Murray-Tuite (2006) proposed a user equilibrium and system optimum metrics using adaptability, safety, mobility, and recovery as the dimensions to minimize the travel time. Madni and Jackson (2009) proposed a conceptual framework to analyze disruption and provide principles to build a resilient system based on lessons learned. However, this conceptual technique is not exclusive to transportation infrastructure. Using infrastructure type and condition, geographical location, the likelihood of disaster, and disaster type as dimensions, Croope and McNeil (2011) developed a critical infrastructure resilience decision support system (CIR-DSS) to provide cost-benefit alternative strategies making the recovery and mitigation phase more efficient. This model uses the transportation network as an example of critical infrastructure (CIs), but it is not exclusive to transportation infrastructure systems. Moreover, this model only focuses on the recovery and mitigation phase. Heaslip et al. (2009) proposed a conceptual methodology and Freckelton et al. (2012) expanded the methodology to measure the individual resilience, community resilience, economic resilience, and recovery ability of transportation networks. However, this methodology mainly focuses on the network characteristics of the transportation infrastructure instead of focusing on physical characteristics. Liao et al. (2018) proposed a resilience optimization model where they assumed that the time interval among occurrence of the disaster, maximum damage propagation, gradual recovery, and full recovery are equal. However, time to reach these four stages might not always be equal. Additionally, no universal agreement on quantifying transportation resilience is made (Liao et al., 2018; Safapour et al., 2020c).

4.3.5. Summary

In summary, the above discussions demonstrate that various sectors have different definitions of resilience. Moreover, different researchers from the same sector have proposed different definitions of resilience. Yet, current literature is unable to provide a universal definition of resilience in transportation infrastructures (Rouhanizadeh and Kermanshachi, 2021c). To quantify the resilience level of physical infrastructure in the transportation sector, it is essential to prepare a list of resilience measuring dimensions (Rouhanizadeh and Kermanshachi, 2020b). The majority of the above-mentioned dimensions are unable to interpret the level of resilience when it comes to the physical properties of transportation networks (Pamidimukkala et al., 2020). Moreover, those dimensions focus on traffic behavior instead of the characteristics of the road network. Hence, a list of resilience measuring dimensions must be prepared to quantify the resilience of the physical characteristics in transportation infrastructure.

4.4. Methodology

4.4.1. Research Outline

Figure 4-2 shows the five-step methodology that was adopted to fulfill the purpose of this study. A comprehensive literature review was conducted in the first step to understand the condition of the existing literature regarding the resilience of the transportation infrastructure projects. Resilience is a new term in the field of transportation, hence, articles with publication years equal to or greater than 2000 were focused on. Preliminary search resulted in 600 articles, from which 372 articles were shortlisted based on the scope of the study among which 109 articles were related to resilience in transportation infrastructures. The second step focused on preparing a database by collecting information from the shortlisted articles. In the third step, a survey was developed supported by the literature to gain expert opinion. The survey was pilot tested and reviewed by the Institutional Review Board (IRB) for appropriateness and send to target participants through electronic media. After multiple follow-up emails, 92 valid responses were collected. Demographic data collected from the survey showed key characteristics of the participants. Multiple statistical tests were performed on the collected data to identify, rank and weight significant variables. Based on the weighted variables a decision-making tool was developed.

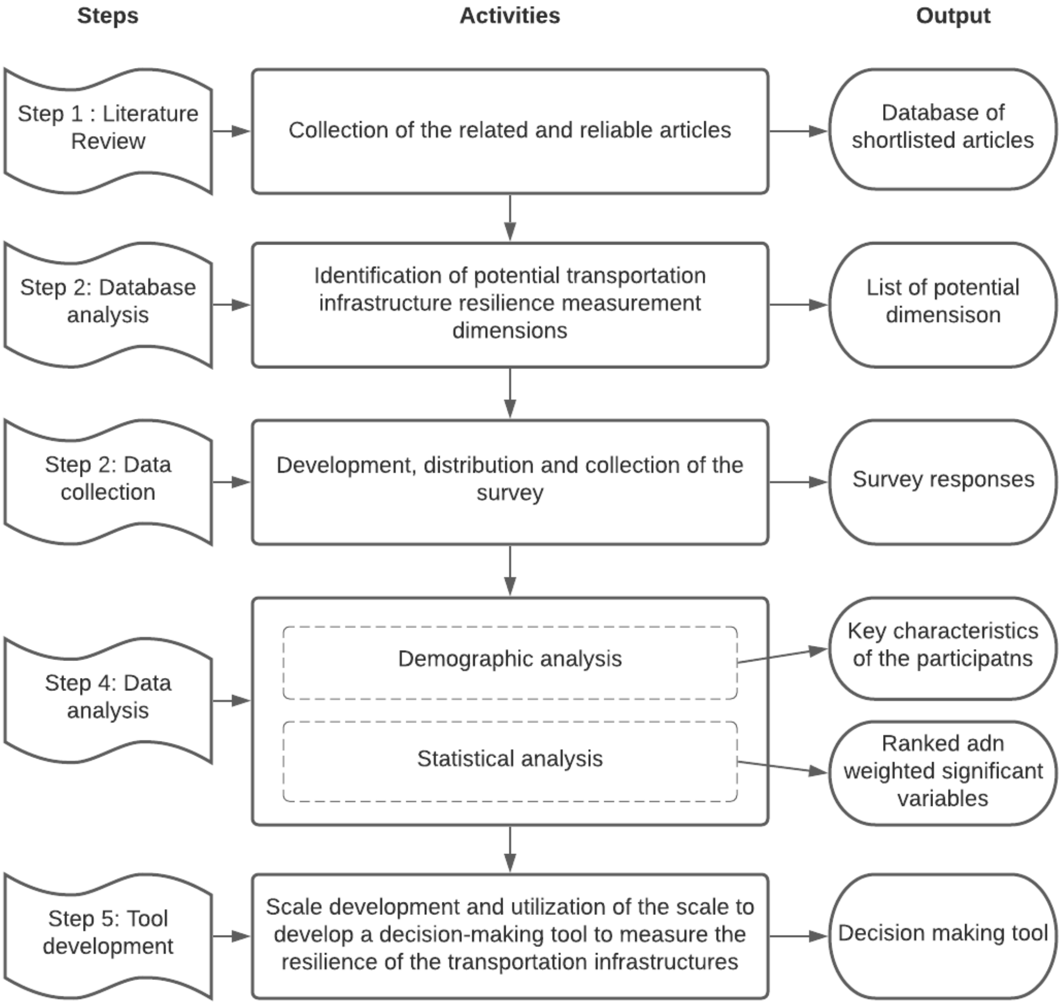
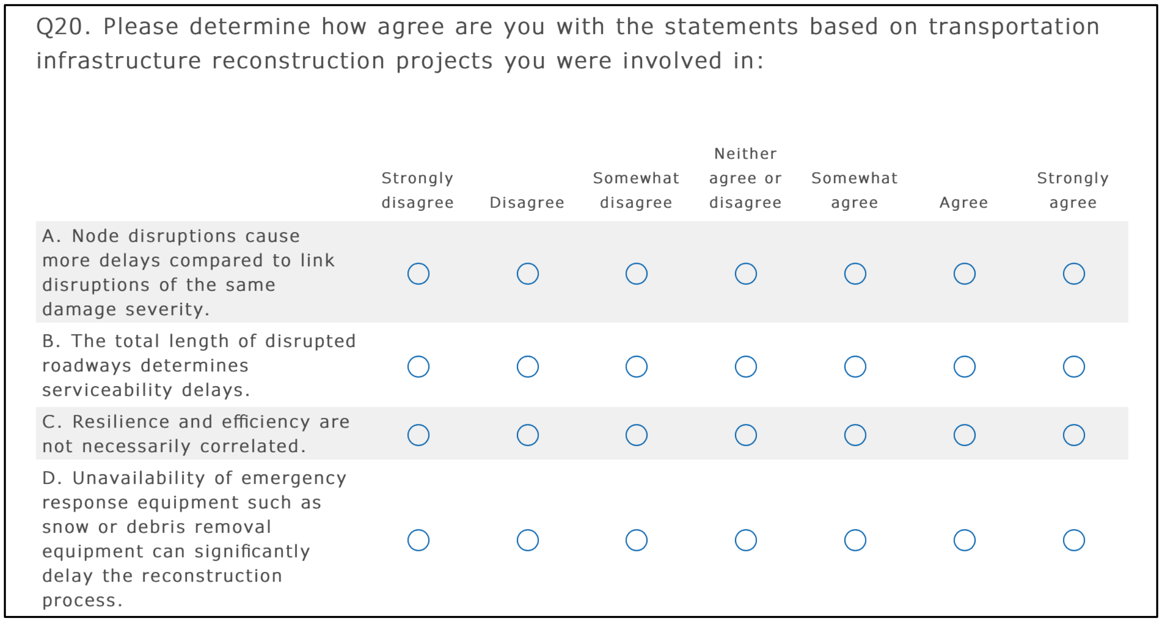


Figure 4-2 Research methodology

4.4.2. Survey Administration

Related and reliable resources including journal papers, conference proceedings, dissertations and theses, and research reports were collected. The articles were collected through keywords search method using search engines like Google Scholar, Web of Science, JSTOR, Science Direct, ProQuest, SciFinder. The few example keywords which were used are as follows: resilience, resilience system, disaster resilience, resilience indicator, resilience index, resilience measurement, resilience measuring framework, and resilience in the transportation system. Resilience has been analyzed for more than 50 years; however, to be practical and to match the scope of the study, only articles published after the year 2000 were focused upon. Initially, 600 articles were collected, and based on the study of the abstract 372 articles were short-listed for systematic content analysis. Content analysis was performed in the following two stages. Within the first stage of scrutinization, collected articles were analyzed, the necessary information was recorded, and the basic information about the articles was collected in a tabular form to prepare a database for the study. The second stage of scrutinization begins with the shortlisting of the studied articles. As one of the objectives of this study is to focus on resilience in transportation infrastructure, related articles were shortlisted before starting the second stage of scrutinization. A total of 109 articles were shortlisted which were related to transportation engineering at this point. Each article was studied thoroughly, and necessary information was collected and stored in the database. Based on the collected information, a list of 20 potential dimensions to measure the resilience of the transportation structures was prepared. The survey consisted of 43 questions. To make the questionnaire more organized and to the point, questions were grouped into the following five sections- (i) Demographic Information, (ii) Project-based Questions, (iii) Resilience Concept, (iv) Resilience Dimensions, (v) Resilience Enhancement Best Practices. The survey included Likert-scale type questions, continuous questions, and open-ended questions. A sample of the survey question is presented in Figure 4-3.



Q20. Please determine how agree are you with the statements based on transportation infrastructure reconstruction projects you were involved in:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
A. Node disruptions cause more delays compared to link disruptions of the same damage severity.	○	○	○	○	○	○	○
B. The total length of disrupted roadways determines serviceability delays.	○	○	○	○	○	○	○
C. Resilience and efficiency are not necessarily correlated.	○	○	○	○	○	○	○
D. Unavailability of emergency response equipment such as snow or debris removal equipment can significantly delay the reconstruction process.	○	○	○	○	○	○	○

Figure 4-3 Survey sample question

The survey was pilot tested to check the appropriateness for the targeted participants. The survey was also reviewed by the Institutional Review Board (IRB) to protect the rights and welfare of the human subjects. After addressing modifications suggested by committee members of the IRB, the survey was approved for distribution and distributed through electronic media. This study required experts' opinion who had experience in working in the field of transportation infrastructures. Hence, the survey was distributed to the people who had an affiliation with the department of transportation (DOTs), Federal Highway Administration (FHWA), State Transportation Agencies (STAs), and Metropolitan Planning Organizations (MPOs) like North Central Texas Council of Governments (NCTCOG), etc. After a couple of reminder emails, 92 valid responses were received.

4.4.3. Statistical tests to be performed

4.3.1.1. Kruskal-Wallis test

The Kruskal-Wallis test determines whether there is a significant difference between averages of the actual observed value and expected one. This test is used for Likert scale questions (ordinal seven-point scale), where it could not necessarily be assumed that the data follows a normal distribution (Kruskal and Wallis, 1952). The following assumptions are made for this test:

- The two groups follow an identically scaled distribution: and
- Each Project is independent of the other projects.

The following equation is used for the Kruskal-Wallis test.

$$H = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_i - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i} \left(r_{ij} - \bar{r}\right)^2} \qquad \text{(Eq. 1)}$$

Where,

n_i is the number of observations in group i

r_{ij} is the rank,

N is the total number of observations in all groups,

$\bar{r}_i$ is the average rank of all observations in group i, and

$\bar{r}$ is the average of all r_{ij}.

4.3.1.2. Two-sample t-test

The two-sample t-test is used where the collected response data are counts or numerical values (Rasch et al., 2011). It is one of the most commonly used tests to determine whether the two independent groups with normal distribution have significant differences in their average values or not. The following assumptions are made for this test:

- The two groups follow a normal distribution, and
- Each Project is independent of the other projects.

The following equations are used for the two-sample t-test:

$$t = \frac{\bar{y}_1 - \bar{y}_2}{s}\sqrt{\frac{n_1 n_2}{n_1 + n_2}} \qquad \text{(Eq. 2)}$$

$$s = \frac{\sum_{i=1}^{n_1}(y_{1i} - \bar{y}_1) + \sum_{i=1}^{n_2}(y_{2i} - \bar{y}_2)}{n_1 + n_2 - 2} \qquad \text{(Eq. 3)}$$

Where,

y is each of our focused variables,

n is the number of variables in a group,

Numerical numbers are population 1 and population 2, and

s is the standard deviation between two groups.

4.3.1.3. Chi-squared test

This test is used for survey questions with binary responses (e.g. “Yes” or “No” response), testing whether the observed frequencies of “Yes” or “No” are equal for both targeted groups (Franke et al., 2012). The following assumption is made for this test:

- Each project is independent of the other projects.

The following equation is used to conduct the Chi-squared test:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}, \qquad \text{(Eq. 4)}$$

Where,

N is the number of cells in the table,

O is the observed value, and

E is the expected value.

4.3.1.4. Cohen's d method

Cohen's d method can measure the effect size of two independent groups. The following equation is used to determine Cohen's d values (Wilcox, 2019).

$$d = \frac{\bar{X}_1 - \bar{X}_2}{S} \qquad \text{(Eq. 5)}$$

$$S^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \qquad \text{(Eq. 6)}$$

Where,

X_1 and X_2 are two independent variables,

n is the sample size, and

s is the standard deviation.

Cohen's d values are normalized and distributed corresponding to 1 for better understanding. Based on the normalized values, the variables are then ranked.

4.3.1.5. Rank-sum method

The rank-sum method is used to determine the weight of a variable corresponding to a list of ranked variables. To obtain the weight of each variable, its corresponding score is initially calculated and assigned. The first variable gets the rank of the last variables as the score. The next variable gets the rank of the second last variable as a score and subsequent variables were scored in this manner. After scoring all the variables, the following equation is used to determine the weight of each variable:

$$w_i = \frac{S_T}{\sum_{j=1}^{N} S_j} \qquad \text{(Eq. 7)}$$

Where,

W_i is the weight, and

S_T is the score associated with each variable.

4.5. Identification of Resilience Dimensions in Transportation Infrastructures

After performing a comprehensive review of existing literature on resilience dimensions in transportation infrastructure, it was concluded that the resilience of transportation infrastructure needs to be researched and investigated from the point of view of construction and reconstruction factors. Based on this perspective, a list of potential resilience measuring dimensions for the transportation infrastructure was developed (Table 4-2).

Table 4-2 Proposed dimensions to measure the resilience of the transportation infrastructure system

#	Dimensions	Description	Reference
1	Number of nodes (intersections)	A disrupted node will create more delay compared to a disrupted roadway in a network under the same severity disaster. Hence, lowering nodes will enhance the resilience of the network by reducing the level of disruption.	Zhang et al., 2017; Ganin et al., 2019
2	Length of the link (roadway without nodes)	A longer roadway means lesser nodes and lesser nodes indicates a lesser possibility of disruption under disaster. hence, a longer roadway will enhance the resilience of the network.	Ganin et al., 2019
3	Length of the disrupted link	The longer length of destruction on the roadway indicates the creation of longer serviceability delays. Hence, the total length of the disruption is a measure of resilience.	Ganin et al., 2019
4	Delay	It is the difference between travel time under normal conditions and over-loaded conditions. The over-loaded condition usually happens after a disaster.	Ganin et al., 2019
5	Type of investment	Investment focused on eliminating delays under normal conditions will make the network strong under day-to-day activities but will make it weak under extreme conditions.	Ganin et al., 2017; Liao et al., 2018
6	Existence of optional routes	The number of available optional routes will increase the redundancy of the network which will help in gaining regular functioning of the network after a disaster.	Wan et al., 2018; Sun et al. 2020
7	Access to the resource	Predefined access routes or options for the non-machinery (materiel and human) materials will reduce the waiting time for the resources after a disaster which will reduce the overall recovery time.	Wan et al., 2018
8	Storing the resource	The safe storage of resources required to reconstruct the affected roadway will have a positive impact on the resilience of the transportation infrastructure networks.	Ganin et al., 2017; Wan et al., 2018
9	Previous disaster experience	Previous disaster handling experience will help the authority become more efficient and prompt during the response and recovery period of the disaster.	Wan et al., 2018
10	Organizational processes	Having a strong balance inside the organization will help in handling disastrous events more efficiently.	Liao et al., 2018
11	Information dissemination	Transferring proper information at a fast pace when needed can significantly help management to take prompt decisions to handle the disaster.	Liao et al., 2018
12	Disaster database	A comprehensive disaster database will help in preparedness as well as recovery stages.	Goidel et al., 2019; Liao et al., 2018

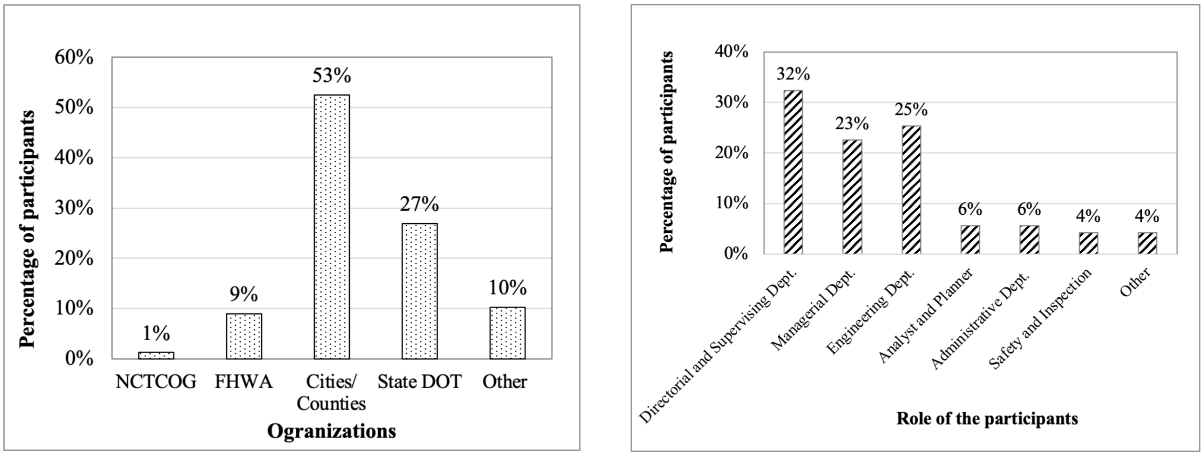
13	Availability of budget	Having a dedicated budget for strengthening activities will ensure that the infrastructure handles disasters with less impact.	Liao et al., 2018
14	Preparedness actions	A preparedness action has the ability to reduce cost and time of the corresponding recovery action.	Wan et al., 2018; Liao et al., 2018
15	Distance from the epicenter	The intensity of the impact of the disaster will lessen with the increase of distance of the infrastructure from the epicenter.	Li et al., 2016
16	Lane number	Having multiple lane gives the opportunity to make one lane into a reversible lane to ensure mobility of the vehicles.	Sun et al., 2020
17	Learning from historical data	Historical data will make it possible to predict the level of disruption and hence help in better preparing to handle the disaster.	Besinovic, 2020
18	Emergency response equipment	Having enough inventory of emergency response equipment can help in recovery activities.	Ganin et al., 2017
19	Resource allocation	Proper allocation of resources in maintenance as well as resilience enhancement activities is needed to reduce cost and time of recovery after a disaster.	Liao et al., 2018
20	Emergency Nodes, Normal Nodes	Taking extra care of emergency nodes with fire station, hospitals etc. will help in faster recovery after a disaster.	Zhang et al., 2017

The above dimensions were studied thoroughly, and to better understand the impact of each dimension on the resilience of the transportation infrastructures, they were elaborated into 37 variables and categorized into six categories- (i) structural, (ii) construction and management, (iii) knowledge and experience, (iv) data related, (v) resources, and (vi) funding and investment. It should be noted that some of the above-mentioned dimensions were divided into two or more variables for resilience measurement purposes.

4.6. Descriptive Data Analysis

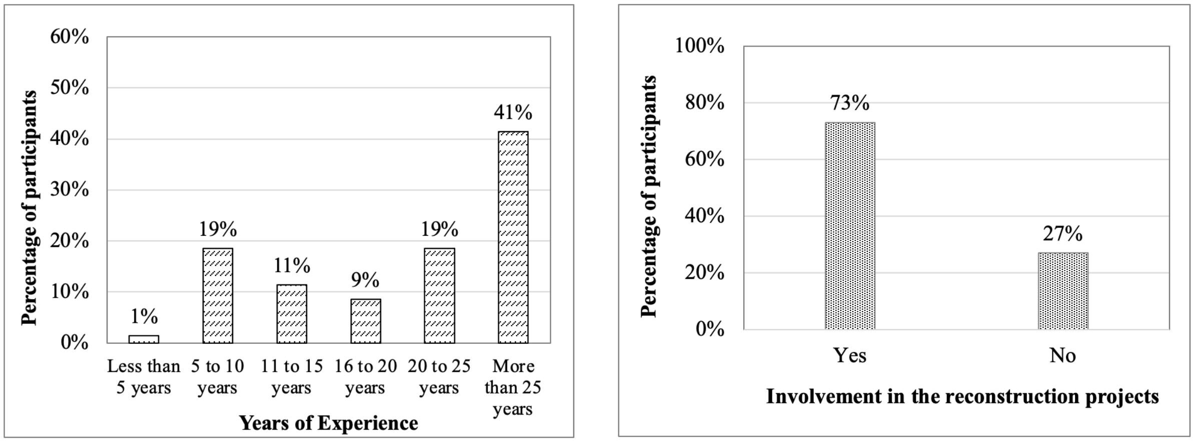
4.5.1. Participants' Demographic Information

The target of the research team was to collect information from experts who are working in different state, national, and international transportation agencies. Figure 4-4a shows that the majority (53%) of the participants are from the cities/counties. 27% of the participants are working or worked in the State DOT. 9% of the participants were from Federal Highway Administration (FHWA). Figure 4-4b shows that most of the participants are from the directorial and supervising department which include director, deputy director, program supervisor, or similar positions. The managerial department had 23% of the participants including project manager, program manager, engineer manager, etc. The engineering department had people who work in different engineering roles like project engineer, city engineer, area engineer, traffic engineer, etc. The rest of the participants were from analyst and planner departments, administrative departments, safety, and inspection departments, and other categories. Figure 4-4c shows the years of work experience for the participants. Many of the participants (60%) have worked in the field of transportation for more than 20 years. Figure 4-4d shows the distribution of the survey respondents based on their involvement in a reconstruction project due to a disaster. As demonstrated in this figure, 73% of the participants were involved in such reconstruction projects during their careers.



a. Participants' organization

b. Role in their organization



c. Years of experience

d. Involvement in reconstruction projects

Figure 4-4 Distribution of the participants based on demographic information

4.5.2. Characteristics of the Reconstruction Projects

Experts included as participants in this study had experience in different kinds of reconstruction projects. Table 4-3 shows that 50% of the participants worked on projects influenced by flood and 25% of the participants worked on projects influenced by the hurricane. Participants also had experience in working in projects influenced by extreme heat/cold, landslides, wildfires, etc. In addition, 66% of the participants had experience in working in roadway reconstruction projects, 22% had worked on highway reconstruction projects. Other types of reconstruction projects that were included in this study are bridge and ports and harbors reconstruction. Also, 26% of the participants had experience in handling big projects with a value of more than $25 million, and 22% of the participants had experience in handling projects with a value less than $1 million.

Table 4-3 Description of reconstruction projects

Category	Types	Percentage
Disaster types	Flood	50%
	Hurricane	25%
	Wildfires	5%
	Extreme heat/cold	5%
	Landslides	5%
	Erosion over time	5%
	Bridge hit causing span to collapse	5%
Project types	Roadway	66%
	Highway	22%
	Bridge	10%
	Ports and harbors	2%
Project value	Less than $1 million	22%
	$1 million to $5 million	26%
	$6 million to $10 million	11%
	$11 million to $15 million	2%
	$16 million to $20 million	8%
	$20 million to $25 million	5%
	More than $25 million	26%

4.6. Statistical Data Analysis

4.6.1. Identification of Significant Variables

The distributed survey described contained Likert-scale and continuous questions. The researchers performed the Kruskal-Wallis test and two-sample t-test to identify the significant resilience measurement variables. The data set was divided into two groups based on participants' involvement in the reconstruction projects. Table 4-4 shows the outcomes of the statistical analysis performed to calculate the significance level of each potential resilience measurement variable.

As shown in Table 4-4, within the structural category, seven variables were found to be significant with p-values of less than 0.1. Results indicated that experts believe the length of a disrupted roadway has a significant impact on the reconstruction process and duration, and therefore, it reduces the resilience of a roadway. In addition, the length of the link, number of lanes, number of optional routes, having a railroad crossing, remoteness of the project, and distance of the link/node from the affected area also affect the resilience of the transportation infrastructure.

For the construction and management category, there were three significant variables with p-values of less than 0.1. Ideally, it is vital to start the reconstruction work as soon as possible; however, it is often impossible to initiate the work right away for various reasons such as unavailability of emergency resources, lack of access to the disaster-affected area, lack of information, etc. Such delays make the reconstruction process more difficult and increase the recovery time. Moreover, when possible preventive actions to enhance the resilience of infrastructure are not integrated into the maintenance planning phase, structures become more vulnerable to upcoming disasters. In addition, reconstruction processes might be further delayed if the integrated assets of the roadway have ownership challenges and there is a dispute in accountability among the owners. These factors highly affect the resilience level of transportation infrastructure.

Table 4-4 Significance test results for resilience measurement dimensions

#	Resilience Dimensions	Corresponding P-values
Structural Category		
1	Number of nodes	0.918
2	The total length of the disrupted roadway	0.094*
3	Length of the link	0.055*
4	Number of lanes	0.08*
5	Number of optional routes	0.083*
6	Emergency nodes	0.872

7	Having a railroad crossing	0.074*
8	Distance of the link/node from the affected area	0.066*
9	Remoteness of the project	0.083*
Construction and Management Category		
10	Time to start reconstruction works	0.086*
11	Information dissemination	0.967
12	Periodical review system for emergency resources	0.641
13	Ownership of integrated infrastructure assets	0.008**
14	Frequency of integration of resilience enhancing activities into the maintenance planning	0.054*
Knowledge and Experience Category		
15	Educational platform on resilience for infrastructure	0.067*
16	Company employees' knowledge of resilience	0.097*
17	Previous disaster experience	0.851
18	Informed project manager about emergency resources	0.966
19	Frequency of evaluation of resilience in the project	0.017**
20	Level of damage	0.492
Data Category		
21	Availability of previous disaster data for the roadway	0.021**
22	Access to previous disaster data for the roadway	0.071*
23	Database of historical resilience enhancement activities and their associated costs.	0.807
Resources Category		
24	Availability of emergency response equipment	0.091*
25	Storing the resources	0.517
26	Accessibility to non-machinery resources (human and materials resources)	0.012**
27	Shortage of human resource	0.969
28	Shortage of material resources	0.990
Funding and Investment Category		
29	Availability of funding	0.385
30	Regular funding to resilience enhancement activities	0.001***
31	Time of allocation of funding	0.001***
32	Considering resilience as part of the investment decision-making process	0.391
33	Involvement in the investment decision-making process	0.949
34	Resilience investment with new projects	0.012**
35	Frequency of investing in resilience enhancing activities	0.054*

"*" denotes 90% confidence level, "**" denotes 95% confidence level, "***" denotes 99% confidence level

Within the knowledge and experience category, there were three significant variables with p-values of less than 0.1. When the responsible decision-maker on a roadway network is familiar with the concept of resilience, that person not only would be willing to take the initiatives to increase the resilience level of the infrastructure but also would be interested in investing in resilience enhancement activities. Hence, providing an educational platform to learn about the concept of resilience, along with known approaches to measure resilience, would be beneficial for the project. Moreover, when an organization quantifies and monitors the resilience level of their infrastructure on a regular basis, it would help them apply proper practices for roadways with low resilience levels.

For the data category of resilience measurement dimensions, two significant variables were found with p-values of less than 0.1. Both identified dimensions are related to the historical data. Availability of previous data would facilitate the prediction of the future possibility of disaster risk and also help in assessing probable damages due to the occurrence of this disaster. Such activities would help in taking preventive measures to reduce the cost of restorative activities after the disaster.

Within the resources category of resilience measurement dimensions, two significant variables were found with p-values of less than 0.1. Availability of emergency response equipment such as debris removal equipment would help the first-hand responders to handle the disaster-affected area. In other words, keeping emergency resources in easily accessible storage could expedite the reconstruction process after a disaster. Hence, the availability of emergency response equipment and access to emergency resources are indicators of the resilience level in transportation infrastructures.

For the funding and investment category of resilience measurement dimensions, four significant variables were found with p-values of less than 0.1. Timely authorization of funding to resilience enhancement activities would ensure that the infrastructure has the capacity to absorb the negative impact of a disaster and bounce back to a satisfactory level of operation within a short period. Moreover, investment in resilience activities should be considered whenever a new project is being planned.

4.6.2. Weighing and Ranking of Significant Variables

Total of 21 variables are found to be significant. Cohen's d method was used to determine the effect size of the significant variables. Cohen's d values were normalized into their corresponding ratios to rank the identified resilience measurement dimensions with the most impact on the resilience level of transportation infrastructure to the least impact. For the next step, it was necessary to determine the weights of identified resilience measurement dimensions since the effects of the identified factors on the resilience of the transportation infrastructures are not equally distributed. The rank-sum method was used to define the weights for each dimension. Irrespective of the categories, 21 identified variables were ranked based on normalized Cohen's d value. Then each variable was given a score based on their calculated rank. The first variable was given a score of 21, the second variable was given a score of 20, and subsequent variables were scored in a similar way. The last variable was given a score of 1. Universal weight was determined by taking the ratio of the score of individual dimensions and the summation of all the scores. Results of the above-mentioned calculations are shown in Table 4-5.

As shown in Table 4-5, the “resilience investment with new project” variable received the highest weight of 0.091. The second-highest weighted dimension is “the importance of previous disaster data for the roadway” with a weight of 0.087.

Table 4-5 Universal rankings of the resilience measurement dimensions

#	Resilience Measurement Dimensions	Normalized Cohen's d value	Rank	Score	Weight
35	Resilience investment with new projects	0.0859	1	21	0.091
22	Availability of previous disaster data for the roadway	0.0757	2	20	0.087
11	Time to start reconstruction works	0.0657	3	19	0.082
3	Length of the link	0.0649	4	18	0.078
5	Number of optional routes	0.0612	5	17	0.074
23	Access to previous disaster data for the roadway	0.0601	6	16	0.069
15	Ownership of integrated infrastructure assets	0.0554	7	15	0.065
27	Availability of emergency response equipment	0.0552	8	14	0.061
7	Having a railroad crossing	0.0525	9	13	0.056
4	Number of lanes	0.0523	10	12	0.052
31	Regular funding to resilience enhancement activities	0.0499	11	11	0.048
32	Time of allocation of funding	0.0499	12	10	0.043
17	Company employees’ knowledge of resilience	0.0480	13	9	0.039
36	Frequency of investing in resilience enhancing activities	0.0463	14	8	0.035
8	Remoteness of the project	0.0449	15	7	0.030
2	Total length of the disrupted roadway	0.0339	16	6	0.026
29	Accessibility to non-machinery resources (human and material)	0.0281	17	5	0.022
21	Frequency of evaluation of resilience in the project	0.0224	18	4	0.017
16	Educational platform on resilience for infrastructure	0.0218	19	3	0.013
13	Frequency of integration of resilience enhancing activities into the maintenance planning	0.0214	20	2	0.009
9	Distance of the link/node from the affected area	0.0045	21	1	0.004

4.7. Development of the Decision-making Tool

4.7.1. Development of the scale

To fulfill the aims of this project, ranked and weighted resilience dimensions were used to develop a decision-support tool to measure the relative resilience of the transportation infrastructure. The tool will have a comprehensive scale so that the users can choose the most appropriate option to better resonate with the level of resilience of the infrastructure.

Each dimension was scaled based on three major definitions. For example, the first variable which is resilience investment for new projects is a dimension that indicates when the resilience investment is being authorized for new projects. Each measure was scaled in three scores, with the first measure being 1-3, the second measure being 4-6 and the third measure being 7-9. In a nutshell, each dimension was defined in three measures and scored from 1-9, with "1" being the least impact and "9" being the most impact in indicating resilience. All 21 variables were defined in such three measures and nine scores, which are shown in Table 4-6.

4.7.2. Providing resilience measurement input

Table 4-6 displays the resilience measurement matrix which can be used to collect the inputs by the user. Users will have the option to score each resilience measurement dimension from "1" to "9" based on the characteristics of the project. If any dimension is not related to a particular project, users will have the option to choose N/A in the score selection column which will establish the score zero for that variable. Additionally, users will have the option to provide comments and/or additional information corresponding to resilience dimensions in the comment section.

Table 4-6 Resilience measurement matrix

#	Dimensions		Score									Score selection	Comments
1	Resilience investment with new projects	Scale	Never				Sometime				Always		
			1	2	3	4	5	6	7	8	9		
		Measure	Rarely			Often time			Regular				
2	Availability of previous disaster data for the roadway	Scale	None				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Limited data availability			Just enough data were available			Data were recorded elaborately				
3	Time to start reconstruction works	Scale	Long				Medium				Short		
			1	2	3	4	5	6	7	8	9		
		Measure	After a long time			After a while			Immediate				
4	Length of the link	Scale	Long				Medium				Short		
			1	2	3	4	5	6	7	8	9		
		Measure	Long length			Medium length			Short length				
5	Number of optional routes	Scale	None				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Low number			Medium number			High number				
6	Access to previous disaster data for the roadway	Scale	Hard				Medium				Easy		
			1	2	3	4	5	6	7	8	9		
		Measure	Difficult to access			Access with permission			Easily accessible				
7	Ownership of integrated infrastructure assets	Scale	High				Medium				Low		
			1	2	3	4	5	6	7	8	9		
		Measure	Multiple ownership			Limited number of ownerships			Few ownership				
8		Scale	None				Medium				High		

	Availability of emergency response equipment		1	2	3	4	5	6	7	8	9		
		Measure	Few available			Enough available			Abundantly available				
9	Having a railroad crossing	Scale	High				Medium				None		
			1	2	3	4	5	6	7	8	9		
		Measure	Multiple crossings			Limited crossings			Few crossings				
10	Number of lanes	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Low number			Medium number			High number				
11	Regular funding to resilience enhancement activities	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Seldom funding			Often funding			Regular funding				
12	Time of allocation of funding	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Only after major disaster			After almost every disaster			Periodical funding irrespective of disaster				
13	Company employees' knowledge of resilience	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	New to work in context of resilience			Had little experience in working in resilience enhancement activities			Expert in resilience enhancing activities				
14	Frequency of investing in resilience enhancing activities	Scale	None				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Invests rarely			Invests sometimes			Invests regularly				
15	Remoteness of the project	Scale	Close				Medium				Far		
			1	2	3	4	5	6	7	8	9		
		Measure	Inside the epicenter			Outside the epicenter			Far from the epicenter				
16		Scale	Long				Medium				Short		

	Total length of the disrupted roadway		1	2	3	4	5	6	7	8	9		
		Measure	Long length			Medium length			Short length				
17	Accessibility to non-machinery resources (human and material)	Scale	High				Medium				Low		
			1	2	3	4	5	6	7	8	9		
		Measure	High difficulty in access			Medium difficulty in access			Easy to access				
18	Frequency of evaluation of resilience in the project	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Seldom quantifies resilience			Often quantifies resilience			Regularly quantifies resilience				
19	Educational platform on resilience for infrastructure	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Seldom review sessions			Sometimes review sessions			Regular review sessions				
20	Frequency of integration of resilience enhancing activities into the maintenance planning	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	Not often			Seldom			Regular				
21	Distance of the link/node from the affected area	Scale	Low				Medium				High		
			1	2	3	4	5	6	7	8	9		
		Measure	In the affected area			Outside the affected area			Far from the affected area				

4.7.4. Output of the resilience measurement tool

The tool will provide output by considering the weighted impact of the resilience dimensions in the transportation infrastructure to be evaluated. It will also consider the level of impact of each dimension on resilience level by utilizing the scores provided by the user. Once the user provides scores in the level of resilience measurement matrix, each score will be multiplied by its corresponding weight which was found using the rank sum method shown in Table 4-5. The research team named this value the “resilience impact-value”. The summation of all the resilience impact values found for different variables for a project will provide the relative level of resilience of that particular project. Proper equations are provided below.

$$\begin{aligned}&Resilience\ impact\ value\ of\ the\ variable\\&\qquad = Weight\ of\ the\ dimension * Score\ of\ the\ dimension\end{aligned} \tag{Eq. 8}$$

$$\begin{aligned}&Level\ of\ resilience\ of\ the\ transportation\ infrastructure\\&\qquad = \sum_{Variable\ 1}^{Variable\ 21} Resileince\ impact\ value\ of\ the\ dimension\end{aligned} \tag{Eq. 9}$$

Table 4-7 shows the output window of the developed decision-making too. The score which will be provided by the users will be in the column named “Score Selection”. Then the “Resilience Impact Value” will be calculated using Eq. 8. The last row shows the “Level of resilience” of the transportation infrastructure network by taking cumulation of resilience impact values that is last column of the table. Different project can utilize this tool to determine the level of resilience of the project and a decision-person can make a judgement by comparing level of resilience of the projects.

Table 4-7 Output window of the tool

#	Resilience Dimensions	Weights	Project 1	
			Score selection	Resilience Impact Value (RIV) = Weights * Score
36	Resilience investment with projects	0.091		
23	Availability of previous disaster data for the roadway	0.087		
11	Time to start reconstruction works	0.082		
3	Length of the link	0.078		
5	Number of optional routes	0.074		
24	Access to previous disaster data for the roadway	0.069		
15	Ownership of integrated infrastructure assets	0.065		
28	Availability of emergency response equipment	0.061		
7	Having a railroad crossing	0.056		
4	Number of lanes	0.052		
32	Regular funding to resilience enhancement activities	0.048		
33	Time of allocation of funding	0.043		
18	Company employees' knowledge on resilience	0.039		
37	Frequency of investing on resilience enhancing activities	0.035		
8	Remoteness of the project	0.03		
2	Total length of the disrupted roadway	0.026		
30	Accessibility to non-machinery resources (human and material)	0.022		
22	Frequency of evaluation resilience in the project	0.017		
16	Educational platform on resilience for infrastructure	0.013		
13	Frequency of integration of resilience enhancing activities into the maintenance planning	0.009		
9	Distance of the link/node from the affected area	0.004		
Resilience level, RL (total of resilience impact values) =				

4.7. Resilience Level

Based on the level of the resilience found using the developed tool, a project can be categorized to have high, medium, and low level of resilience (Table 4-8). The table was developed by assuming that a project had maximum score of the 9 for all the variables to gain the maximum resilience level of 9.00, as well as a project had minimum score of 0 for all the variables to gain minimum resilience score of 0.00. The range from minimum to maximum was divided in three parts to gain a 3 category of resilience for the projects.

Table 4-8 Resilience level of different category projects

Project	Resilience Level	Project Type
Project 1	6.00 – 9.00	High Resilience
Project 2	3.00 – 6.00	Medium Resilience
Project 3	1.00 – 3.00	Low Resilience

4.7. Conclusion and Limitation

The objectives of this study were to identify resilience measurement dimensions for transportation infrastructure and develop a decision-making tool to measure the relative resilience level of the transportation infrastructure. After conducting a comprehensive literature review of over 372 scholarly articles, a list of potential resilience measurement dimensions was prepared. Based on the potential dimensions a survey was prepared and distributed among experts whose expertise are concentrated on the construction and maintenance of transportation infrastructure. Demographic data analysis of the survey results showed that even though 73% of the participants were involved in transportation infrastructure reconstruction and 60% of the participants had more than 20 years of experience in such efforts, only 45% of the participants were familiar with the concept of resilience. The results of the statistical analysis identified 21 significant measurement dimensions which have an impact on the resilience level of transportation infrastructure. It was found that network characteristics (length of the link, number of lanes, number of optional routes, etc.), organizational characteristics (time to start reconstruction work, knowledge of the employee, resilience measurement experience, etc.), and information related to data (previous data availability and data accessibility, etc.) have major impacts on the potential resilience of the transportation infrastructure. Based on these resilience enhancement dimensions; a decision-making tool was developed in this study. The tool has a scoring system from “1” to “9” for each of the variables. Based on the score provided by the user, the tool will provide a relative resilience value for the infrastructure. This model will help practitioners make informed investment decisions and provide the capability to prioritize available funding allocations in efforts to enhance the resilience of transportation infrastructure.

CHAPTER 5

ANALYSIS OF THE RESILIENCE DIMENSIONS AND THEIR IMPACT ON HIGHWAY TRANSPORTATION INFRASTRUCUTRE PROJECTS: ADOPTION OF STRUCTURAL EQUATION MODELING (SEM) TECHNOQUE

This chapter will be submitted as:

Nipa, T. J., & Kermanshachi, S. (2021). Analysis of the Resilience Dimensions and Their Impact on Highway Transportation Infrastrucure Projects: Adoption of Structural Equation Modeling (SEM) Technique.

5.1. Abstract

The recent increase in disasters is making the transportation infrastructure system susceptible to unexpected damage. Discontinuation of services provided by transportation infrastructures will create significant societal, economic, and financial damages. Current literature offers a large number of studies on transportation infrastructure resilience; however, they rarely provide dimensions and measurement models from the construction and management point-of-view. Therefore, this study aims to identify dimensions to measure the resilience of the transportation infrastructures. This study also aims to develop model to establish the impact of identified dimensions on the level of resilience of the transportation infrastructures. To fulfill the aims of this study, a questionnaire was developed which was supported by a comprehensive literature review. 92 valid responses were received and analyzed qualitatively and quantitatively. Exploratory factor analysis (EFA) was performed to identify the constructs and structural equation modeling (SEM) was used to develop the model. Results show that even though the majority of the participants

were involved in the reconstruction of transportation infrastructures and had experience in working in the field of transportation for more than 20 years, only a limited number of participants were familiar with the concept of resilience. It was found that integrated assets have a high impact on the rapidity of the reconstruction projects. The findings of this study will support practitioners and decision-makers in investing and funding appropriate projects for resilience enhancement activities. Also, this study will help practitioners in prioritizing the most impactful component for the resilience level and develop management strategies accordingly.

5.2. Introduction

The dependency of human civilization on critical infrastructures (CI's) is unavoidable. Transportation infrastructures are among the CI's which are especially vulnerable to unpredictable and destructive natural disasters (Liao et al. 2018). Not only frequency but also intensity of natural disaster has increased recently by many fold (Patel et al., 2021; Safapour et al., 2021). Hurricane Irene of 2011 on the East Coast of the U.S damaged more than 500, 2000, and 200 miles respectively of highways, roadways, and railways which resulted in 56 deaths and around $15.6 billion losses (Wan et al., 2018). Hurricane Katrina and hurricane Harvey caused a catastrophic situation for safety and health of reconstruction works (Safapour and Kermanshachi, 2019). In addition, a great monetary price must be paid if the recovery of transportation infrastructures is delayed (Mojtahedi et al. 2017) as the condition of transportation infrastructures highly determines the recovery pace of other sectors including residential buildings and industrial plants of the affected area (Frangopol and Bocchini 2011). On the other hand, a resilient system not only reduces the probability of the failure of the system but also reduces the destruction caused by the disaster and recovery time to reconstruction (Heaslip et al, 2009).

The adverse impact of natural disasters becomes astounding when infrastructures possess a poor resiliency level. Resilience is a term which is been studied for more than half of a century. The first conceptualization of resilience was occurred by ecologists and eventually, almost all the other application domains addressed the necessity of this terminology (Franchin and Cavalieri, 2015). Hence, several definitions of resilience exist in the literature (Moteff, 2012). The resilience of a system is its ability to bounce back to the predetermined level of performance after a disaster with the shortest possible duration. Hence, the definition of resilience has a static part that focuses on the desired level of performance and a dynamic part that focuses on the speed to achieve that level (Reggiani, 2013). However, to be resilient, the system must be technically, organizationally, economically, and socially resilient. Technical resilience indicates the soundness of the physical properties of the system under the disruptive event. Organizational resilience indicates the competence of the responsible person to handle the decision-making process under the crisis. Economic resilience indicates the availability of monetary resources needed to face and recover from the disaster. Social resilience indicates the ability of the surrounding society to provide primary help to the sufferers. These four sides of resilience are collectively known as TOSE (Labaka et al., 2016). Based on the mentioned classification, this study mainly focuses on technical and organizational resilience from a construction and management point of view.

Over the last few decades, resilience has been studied vigorously to assess damages and performance of infrastructures suffered by disturbing events like natural and/or man-made hazards. Not only researchers but also governments and agencies are harboring an interest in infrastructure resilience. Critical infrastructure resilience is a major objective that is being carried out by The Department of Homeland Security (DHS) for more than a decade (Vugrin et al., 2011). However, only since 2009, transportation resilience has been considered as an independent focus of study

(Wan et al., 2018). In this regard, many models and frameworks related to transportation resilience have already been developed. For example, Faturechi and Miller-Hooks (2014) developed four mathematical formulations in the context of transportation networks focusing on functionality, rapidity, recovery, and flexibility of resilient systems. Freckleton et al. (2012) developed a conceptual framework considering only the level of damage, redundancy, and rapidity of resilience. However, a comprehensive model to measure the resilience of transportation infrastructures considering all dimensions of resiliency is yet to be developed (Liao et al. 2018). Moreover, very few studies have focused on studying transportation infrastructure resilience from the construction and management point of view.

Therefore, this study aims to develop models to measure the resilience level of existing transportation infrastructures. This study identifies terminologies that could increase the resilience level of infrastructures reducing the probability of failures due to extreme weather catastrophes. To fulfill the aim of this study, the following objectives were formulated- identifying the dimensions to measure the resilience of transportation infrastructures and developing models to measure the resilience of transportation infrastructures networks. The findings of this study will help practitioners and decision-makers in deciding critical transportation infrastructure projects to fund and invest in for resilience enhancement activities.

5.3. Literature Review

5.3.1. Disaster Management

Both rate of occurrence and intensity of destruction for man-made as well as natural disasters has increased to a concerning level in recent years (Rouhanizadeh et al., 2020b). Active and complex critical infrastructures (CIs) such as transportation, communication, energy, water, etc. are facing great challenges to continue functioning under the impact of disasters due to their age and vulnerability (Croope and McNeil, 2011). The interdependency characteristic of transportation networks amplifies the susceptibility to damage due to disaster for the transportation systems. A transportation system must undergo four phases of life when hit by a disaster – mitigation, preparedness, response, and recovery. Mitigation and preparedness phases occur before a disaster hits and hence the impacts of disasters can be projected. Based on these projected impacts proper mitigating actions are planned to better prepare for the disasters. Response phase lasts until immediately after the disaster, however, the recovery phase extends till the performance is being gained to a satisfactory level. Recovery phase becomes is specially critical since it deals with chaotic environment (Safapour and Kermanshachi, 2021a; Kermanshachi et al., 2020b; Rouhanizadeh and Kermanshachi, 2021d). Decisions that are made during the mitigating and preparedness phase highly impact the time and effectiveness of the response and recovery phase. Throughout the literature, resilience, and robustness is being mentioned as one of the most effective preparedness actions to reduce cost and schedule of recovery phase (Faturechi and Miller-Hooks, 2015).

Moreover, massive destruction with significant economic loss due to disasters like Hurricane Katrina, Hurricane Sandy, etc. has forced national priorities in the US from risk-based management to resilience-based management (Patel et al., 2020b; Safapour and Kermasnahchi., 2021d). Prior management system focuses on the likelihood of occurrence and level of impact of the disaster whereas resilience-based management focuses on integrating measures to improve the inherent capability of the system to provide discontinued functionality even after being affected by a disaster (Faturechi and Miller-hooks, 2015). Such shift of management is necessary for civil infrastructures especially transportation infrastructures (Bostick et al., 2018). This is because discontinued service by transportation infrastructure will increase the indirect cost of disaster remarkably. To ensure and sustain continuous function, constant investment is made for transportation infrastructures. Incorporating the concept of resilience in every phase of the disaster for transportation infrastructures will highly reduce economic loss due to disaster as well as recovery cost afterward.

5.3.2. Concept of Resilience

Renowned ecologist Holling has first conceptualized resilience in 1973 concerning ecological systems and since then the concept of resilience is being studied for more than 5 decades (Holling, 1973). Over the years, many sectors including infrastructures, community, health, etc. have incorporated the concept of resilience in their respective study and defined resilience accordingly (Franchin and Cavalieri, 2015). Hence, current literature provides a significant number of definitions of resilience concerning the field of study (Moteff, 2012). Dick et al. (2019) defined resilience of critical infrastructure as the inherent ability to reduce the negative impact of the disaster by establishing alternative activities and developing emergency responses to undertake during disasters. Lam et al. (2018) provided a straightforward definition of resilience. They claimed that the ability of a community to recover from the damages that occurred due to disaster is the resilience of that community.

The concept of resilience also can be explained by taking static component performance as a function of dynamic component recovery time for a system (Reggiani, 2013). Figure 5-1 shows a system's performance level against time including a disastrous event. Here, Y-axis identifies the level of performance, and the X-axis identifies the time. A system with good resilience capability will have the minimum amount of loss of disruption (minimal difference between p_t and p_0) and will have faster recovery (difference between t_2 and t_3 will be reasonable).

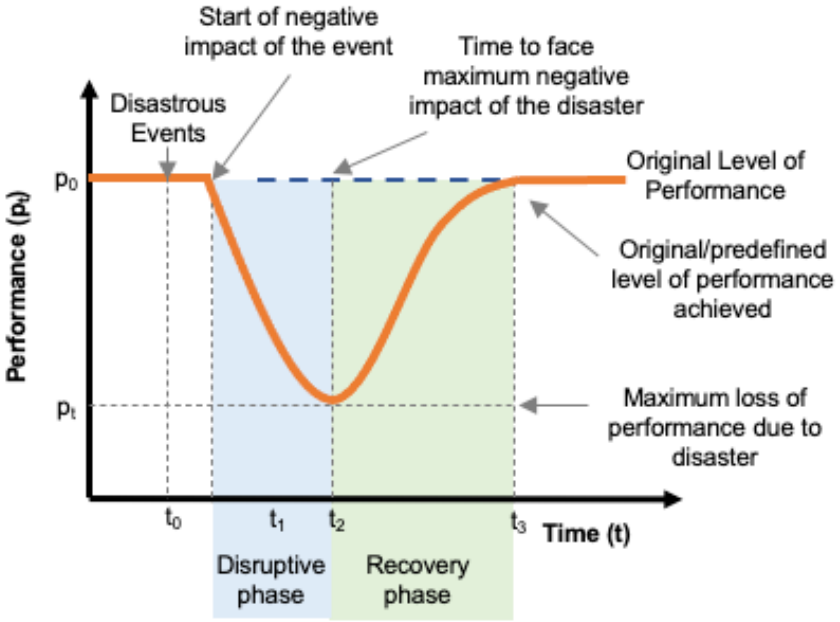


Figure 5-1 Resilience concept

Moreover, throughout the literature, numerous terminologies are being used to define and interpret the concept of resilience by different researchers (Nipa and Kermanshachi 2020; Nipa and Kermanshachi 2021). While integrating resilience in the engineering research, level of functionality was identified as robustness, and recovery time was identified as rapidity by McDaniels et al. (2008). Terms robustness, rapidity, redundancy, and resourcefulness were used by Zhang et al. (2017) while defining road-bridge networks. These four terminologies which are commonly known as 4R are the most common and most used in the research of resilience irrespective of the field of study. Many researchers (Bruneau et al., 2003; Sun et al., 2020) have used 4R in their studies related to resilience. However, with time the usage of resilience has broadened into many sectors hence many more terminologies were identified and adopted based on the usage of the concept. For example, mobility which indicates the network's ability to move vehicles or people from one place to another is an important component of the transportation infrastructure resilience.

5.3.3. Dimensions of Transportation Infrastructures Resilience

The transportation sector has incorporated the concept of resilience as an independent study only since 2009. Since then, it has gained rapid popularity and current literature contains a significant number of related studies. However, not all researcher in this field has used the same terminologies to define resilience neither they used the same dimensions to measure the transportation infrastructure resilience. The most repetitive dimensions that are currently being used throughout the literature to measure the resilience of the transportation infrastructures are the absorptive, adaptive, and restorative capacity of the transportation infrastructures (Figure 5-2). A transportation system with the necessary level of redundancy, efficiency, diversity, strength, adaptability, autonomous components, collaboration, mobility. Safety and rapidity will be technically, organizationally, socially, and economically resilient.

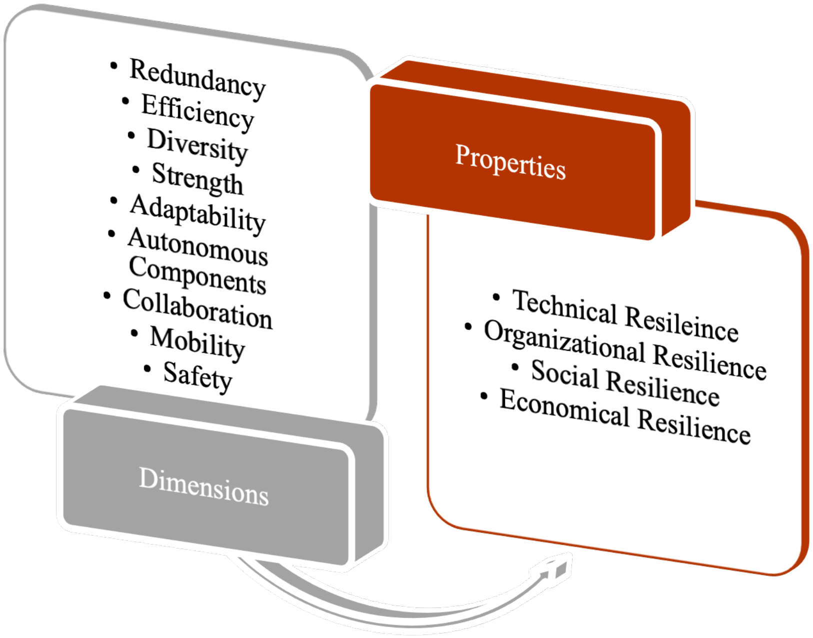


Figure 5-2 Dimensions to measure resilience of transportation infrastructures based on current literature

5.3.4. List of Potential Dimensions

Content analysis resulted in potential dimensions that might be able to indicate the level of resilience of transportation infrastructure. Since the focus of the study is to mainly determine the level of resilience of the roadway network, the most suited dimensions were identified. These potential dimensions were studied and 35 variables in 6 categories were prepared based on the dimensions to develop a survey. Figure 5-3 shows the developed variables. Variables were divided into six categories. Category structural had nine variables collectively which indicate the physical characteristics of the roadway network. The second category is management which has five variables that indicate the condition of the reconstruction works and management system of the authority. The third category is knowledge and exposure which has 6 variables that indicate the level of knowledge of the employees of the management authority. The fourth category data related. This category had three variables that indicate the availability and accessibility of the database related to disaster and resilience activities for a roadway. The fifth category is the resources which included five variables. Collectively these five variables indicate the accessibility and availability of resources. The last category is funding and investment which has seven variables. Collectively they indicate the condition of the funding and investment of the organization.

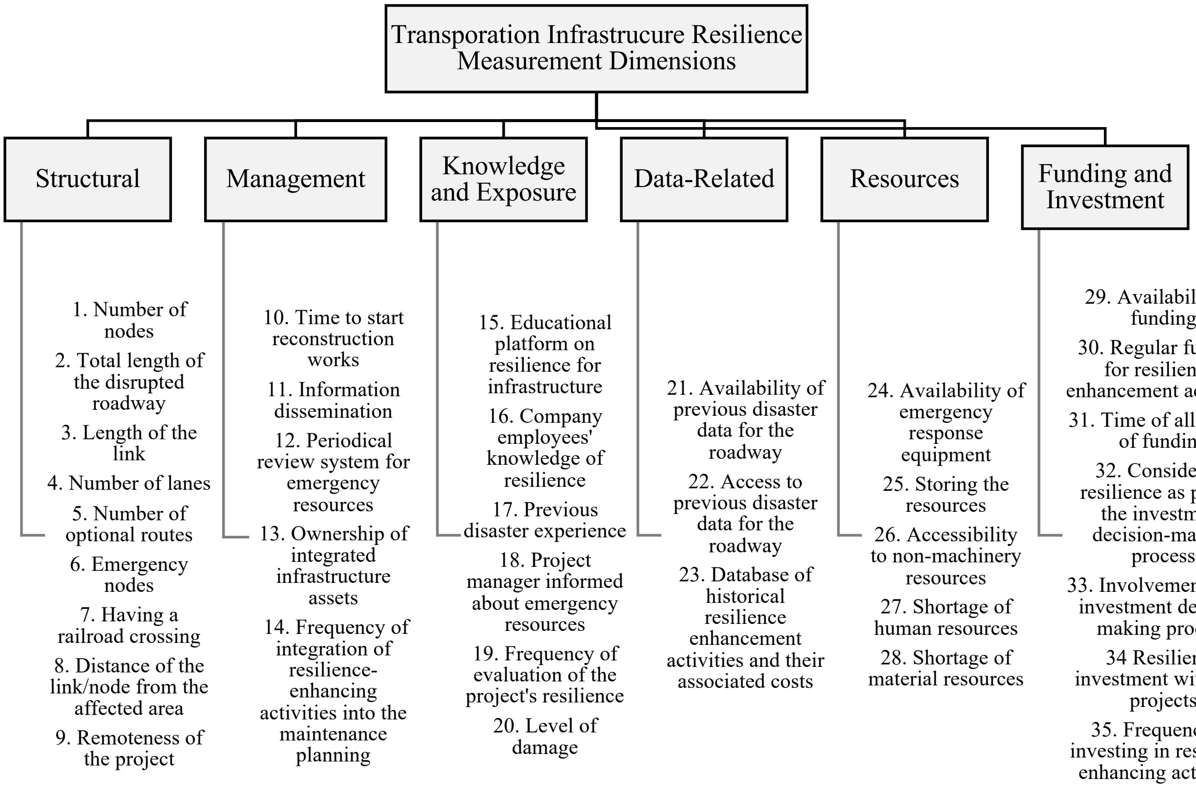


Figure 5-3 Categorized list of variables

5.3.5. Summary

Resilience is rich with various definitions and numerous dimensions, yet current literature does not provide a universal definition of resilience for transportation infrastructures (Rouhanizadeh and Kermanshachi, 2021e). For the purpose of this study, the resilience of transportation infrastructures was defined as the ability to tolerate disturbance while keeping the basic structure and function intact and to recover performance deviation after the disaster within a reasonable schedule and budget.

Moreover, a significant number of dimensions exist throughout the literature to measure and quantify resilience, yet they are not adequate to interpret the resilience level of transportation infrastructures. The majority of these dimensions do not have fixed meaning and countable measure instead they are defined and quantified based on the scope of the study. In addition, the same terminology has been defined in different ways throughout the literature. Moreover, transportation infrastructure resilience has rarely been explored from the construction and management point of view. Hence it is a prerequisite to prepare a list of resilience measuring variables to quantify the level of resilience of the physical segment of the transportation network.

5.4. Methodology

This study followed a five-step methodology shown in Figure 5-4. Step 1 is the literature review, step 2 is database analysis, step 3 is data collection, step 4 is data analysis and step 5 is model development.

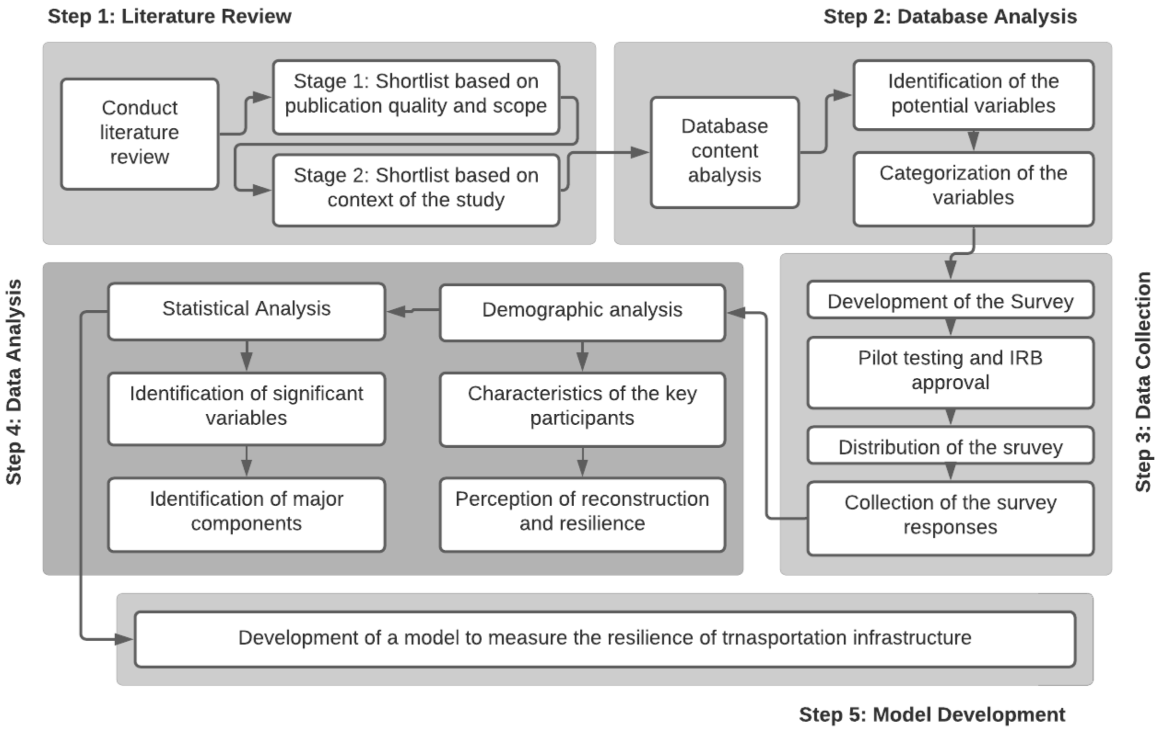


Figure 5-4 Project flow diagram

5.4.1. Literature Collection Process

Keywords search option was used to collect reliable and related scholarly articles for conducting a comprehensive literature review. Keywords like resilience, resilience system, disaster resilience, resilience indicator, resilience index, resilience measurement, resilience measuring framework, and resilience in the transportation system, etc. were used the search through popular search engines like Google Scholar, JSTOR, Web of Science, Science Direct, ProQuest, SciFinder, etc. Several other factors were considered while collecting articles - articles from peer-review sources were prioritized, articles with publication year equal to or later than 2000 were prioritized. The initial search resulted in 600 articles, however, based on the relevance with the scope of the project only 372 articles were shortlisted for content analysis.

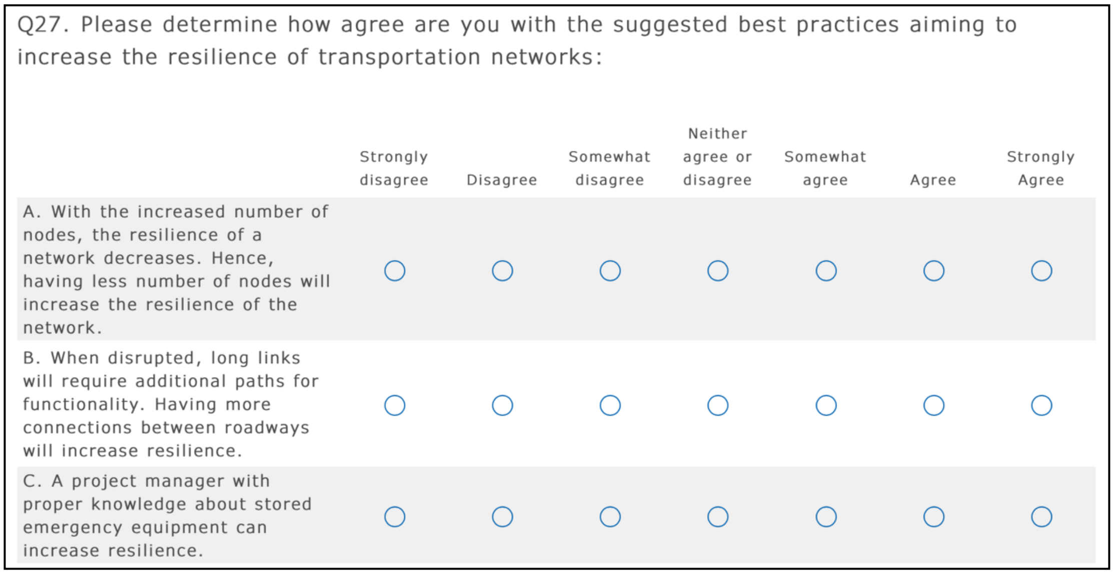
5.4.2. Content Analysis

Content analysis was performed in two stages. First stage content analysis aimed to understand the current literature regarding the current research trend of resilience. During this stage, articles were categorized based on the publication year, number of citations, discipline, geographic location, disaster type. In addition, information regarding the concept of resilience including adopted definitions, characteristics, and dimensions is collected, and a database was prepared. Second stage content analysis was performed over 109 articles that were related to the transportation discipline and mainly discussed the concept of resilience with respect to transportation engineering. After a thorough review of each article, the authors were able to identify the major characteristics of transportation infrastructure resilience.

5.4.3. Survey Administration

5.4.3.1. Survey Development

Experts' opinion was collected using a structured survey. A survey converting variables into questions was prepared. Including demographic questions and questions related to dimensions and best practices, the survey had a total of 43 questions. To make the survey simple and organized for the participants, questions were divided into five sections – i. demographic question, ii. project-based questions, iii. Concept of resilience, iv. resilience dimensions related; v. best practice related. A combination of Likert-scale questions, continuous questions, and open-ended questions was used to prepare the survey. Also, the survey had an introductory part where the authors explained the instruction on how to correctly fill the survey. A sample of the survey questions is provided in Figure 5-5.



Q27. Please determine how agree are you with the suggested best practices aiming to increase the resilience of transportation networks:

	Strongly disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly Agree
A. With the increased number of nodes, the resilience of a network decreases. Hence, having less number of nodes will increase the resilience of the network.	○	○	○	○	○	○	○
B. When disrupted, long links will require additional paths for functionality. Having more connections between roadways will increase resilience.	○	○	○	○	○	○	○
C. A project manager with proper knowledge about stored emergency equipment can increase resilience.	○	○	○	○	○	○	○

Figure 5-5 Sample from the survey

5.4.3.2. Approval, distribution, and collection of the survey

After completion of the survey, it was sent to the institutional review board (IRB) for approval. IRB is the institution that cross-checks every survey/experiment conducted by the institution that includes human subjects in order to make sure that the welfare of humanity is protected, and proper consent of the participants is taken. Authors filled up necessary forms and submitted documents along with the survey to IRB for approval. It was mentioned that the survey participants were adults, and the survey included minimal risk. After multiple modifications suggested by the committee members of the IRB, the survey was approved for distribution.

A list of potential participants for the survey was prepared. The authors mainly focused on experts in the field of transportation. Keeping that in mind, the list mainly consisted of directors and their assistants, engineers, supervisors, FEMA personnel, and other potential participants for the survey. An invitation letter mentioning the instruction for the survey was sent through email to each potential respondent. The letter also explained that participation in the survey was voluntary and there will not be any compensation upon participation in the survey.

The team continued sending reminder emails to the potential participants. After a couple of reminder emails, 92 valid survey responses were collected.

5.4.3.3. Statistical tests to be performed

Since the survey had multiple types of questions including Likert-scale questions, continuous questions, and open-ended questions, authors choose to perform the Kruskal-Wallis test, two-sample t-test and Chi-squared test to identify significant variables. Table 5-1 shows the assumptions for a particular test. Tests are performed to determine whether there is a difference between averages of the actual observed value and expected value.

Table 5-1 Statistical tests

Test	Assumption	Reference
Kruskal-Wallis test	- Two groups follow an identically scaled distribution. - Each project was independent of other projects. - Used for Likert-scale type of questions	Kruskal and Wallis, 1952
Two-sample t-test	- Two projects follow a normal distribution. - Each project was independent of other projects. - Used for response with count or numerical value.	Rasch et al., 2011
Chi-squared test	- Each project is independent of other projects	Franke et al., 2012

A sophisticated tool, Structural Equation Modeling (SEM), was used to examine the impact that each construct identified by the factor analysis had on the others, as well as the resilience level of the transportation infrastructures. SEM has gained popularity recently for developing multivariate relationships and parsimonious models (Wang and Rhemtulla, 2021). Cheng (2001) established the benefits of using SEM over multiple regression modeling techniques by developing a model for training transfers. He found that SEM not only validates hypothesized relationships but also provides new relationships between constructs and parameters based on modification indices. Sambasivan et al. (2017) used SEM in project management and determined the relationship between the cause and effect of delays in the Tanzanian construction industry. They found that SEM was suitable for their study since it is efficient in handling complex dependencies and provides flexibility with sample numbers. Many researchers have suggested sample sizes for SEM analysis. Some have proposed a minimum number of samples (for example, 100 or 200), while some researchers suggested having 5-10 samples per parameter (Cheng and Rhemtulla, 2021). Cheng and Rhemtulla (2021) espoused that such one-size-fits-all recommendations are based on weak empirical studies and work against the flexibility of the SEM model.

5.5. Data Analysis

5.5.1. Qualitative Analysis

5.5.1.1. Demographics of key participants

Keeping the scope of this study in mind, the authors contacted the personnel who were involved with different state, national, and international transportation agencies including different state departments of transportation (DOTs), North Central Texas Council of Governments (NCTCOG), Federal Highway Administration (FHWA), etc. It was found based on the analysis performed over responses that the majority (53%) of the participants had an affiliation with cities/counties (Table 5-2). 27% of the participants were associated with different state DOTs. 9% of the participants had worked with FHWA.

Demographic data regarding respondents' years of experience in working in different transportation agencies were also analyzed (Table 5-2). 41% of the participants had more than 25 years of experience in working in the field of transportation. 19% of the participants had 20 to 25 years of experience in working in the field of transportation. In a nutshell, the majority of the participants were involved in different state, national and international transportation agencies for more than 20 years.

Table 5-2 Distribution of participants based on organization, year of experience, and responsibility

Category	Selections	Percentage
Based on organization	NCTCOG	1%
	FHWA	9%
	Cities/Counties	53%
	State DOT	27%
	Other	10%
Based on the year of experience	Less than 5 years	1%
	5 to 10 years	19%
	11 to 15 years	11%
	16 to 20 years	9%
	20 to 25 years	19%
	More than 25 years	41%
Based on responsibility	Directorial and Supervising Department	32%
	Managerial Department	23%
	Engineering Department	25%
	Analyst and Planner	6%
	Administrative Department	6%
	Safety and Inspection	4%
	Other	4%

People from various levels of authority with varieties of job responsibilities have filled the survey. Table 5-2 shows that 32% of the participants' job responsibilities indicated a position related to the directorial and supervising positions. For example, this category had directors, deputy directors, and program supervisors. 25% and 23% of the participants had performed works that are related to engineering and managerial positions respectively. A few examples of these two categories are project engineer, city engineer, city manager, project manager, program manager, etc. In addition, people from the planning, administrative, safety, and inspection department were in the participant group. However, from the above discussion, it is evident that the majority of the participants had more than 20 years of working experience and were from a relatively higher level of authority.

5.5.1.2. Experience of the participants with the reconstruction projects

The survey had questions related to the involvement in the reconstruction projects. From Figure 5-6, it can be seen that 73% of the participants were involved in the reconstruction of transportation infrastructure at least once in their careers.

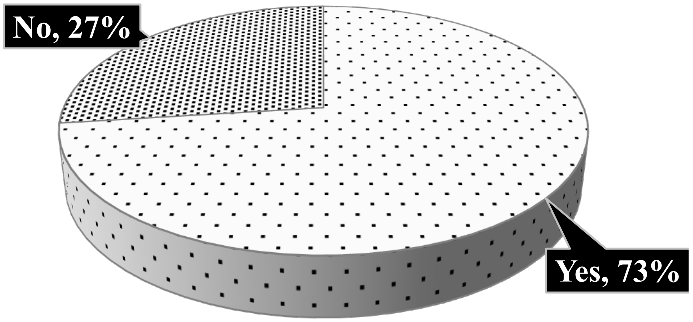
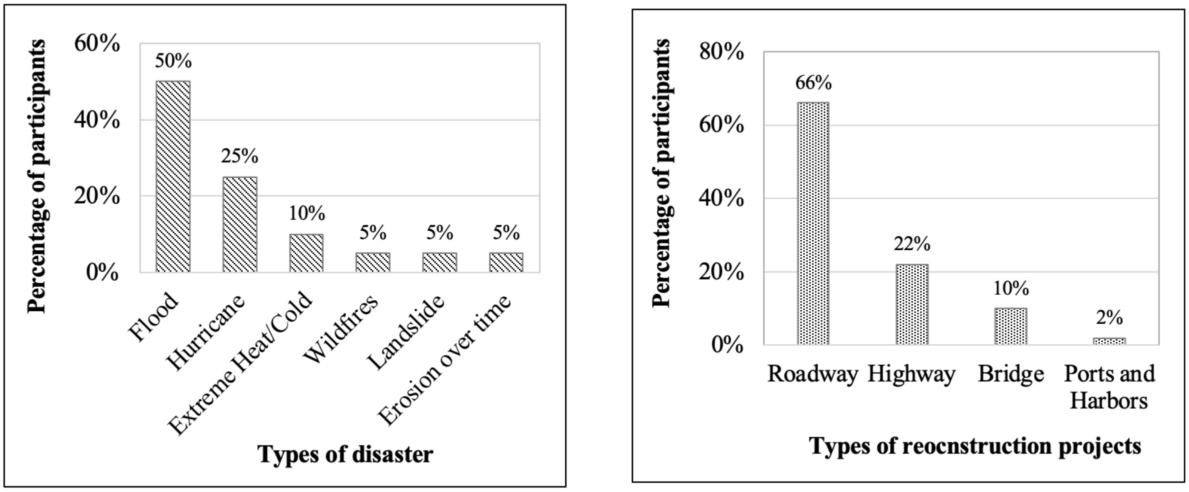


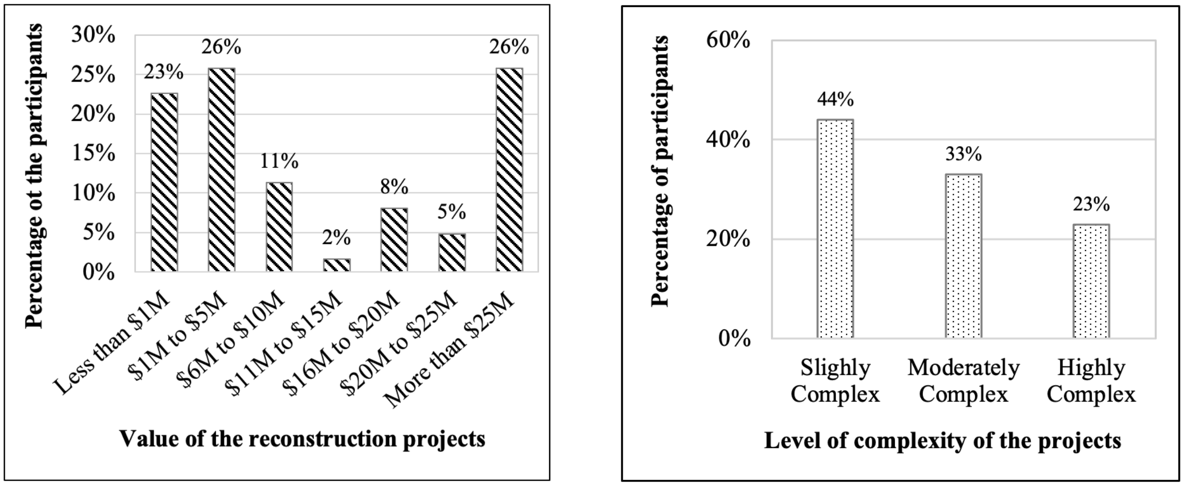
Figure 5-6 Involvement in the reconstruction of transportation infrastructure projects

Figure 5-7 shows that participants had experience in working with projects with a value of less than \$1M (26%) as well as more than \$25M (26%). This indicates that the participants had experience working in projects with a very limited budget as well as projects with a significant budget. Participants also had experience in working in highly complex transportation reconstruction projects (22%). This indicates that the participants had experience in working on simple projects with limited funding as well as a major complex project with a significant budget.



a. **Types of Disasters**

b. **Types of Reconstruction Projects**



c. **Value of the Reconstruction Projects**

d. **Level of Complexity**

Figure 5-7 Distribution of the participants based on their experience with the reconstruction projects

5.5.1.2. Knowledge of the participants about the concept of resilience

The concept of resilience in transportation infrastructures has gained fast popularity. However, to understand this popularity in the context of practitioners, the authors included questions regarding familiarity with the concept of resilience. It was astonishing to find that even though 60% of the participants were involved in the transportation field for more than 20 years, only 45% of participants were aware of resilience (Figure 5-8). 25% of the participants were somewhat familiar with the concept of resilience and 30% of the participants were not familiar with the concept of resilience.

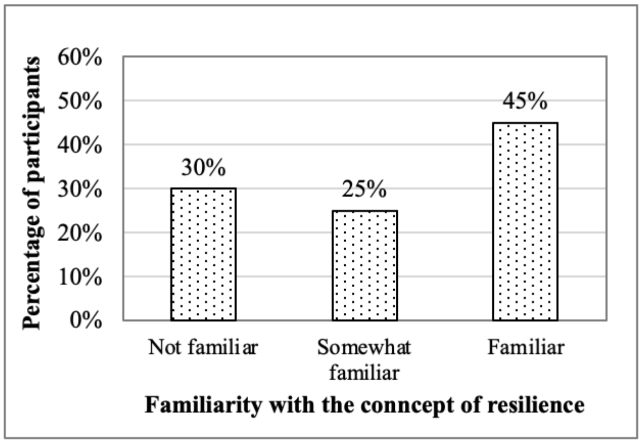


Figure 5-8 Distribution of the Participants based on Familiarity with the Concept of Resilience

5.6. Statistical Analysis

5.6.1. Identifying significant variables

Based on different criteria, significant variables were identified using the Kruskal-Wallis test and two-sample t-test, and results are shown in Table 5-3. Among thirty-five variables, twenty-one variables were found to be significant.

Table 5-3 Significant variables of measurement of transportation infrastructure resilience

Category	#	**Variables**	P-values
Structural	V2	Total length of the disrupted roadway	0.094*
Structural	V3	Length of the link	0.055*
Structural	V4	Number of lanes	0.08*
Structural	V5	Number of optional routes	0.083*
Structural	V7	Having a railroad crossing	0.074*
Structural	V8	Distance of the link/node from the affected area	0.066*
Structural	V9	Remoteness of the project	0.083*
Management	V10	Time to start reconstruction works	0.086*
Management	V13	Ownership of integrated infrastructure assets	0.008**
Management	V14	Frequency of integration of resilience enhancing activities into the maintenance planning	0.054*
Knowledge and Experience	V15	Educational platform on resilience for infrastructure	0.067*
Knowledge and Exposure	V16	Company employees' knowledge of resilience	0.097*
Knowledge and Exposure	V19	Frequency of evaluation of resilience in the project	0.017**
Data-related	V21	Availability of previous disaster data for the roadway	0.021*
Data-related	V22	access to previous disaster data for the roadway	0.071**
Resources	V24	Availability of emergency response equipment	0.091*
Resources	V26	Accessibility to non-machinery resources	0.012**
Funding and Investment	V30	Regular funding to resilience enhancement activities	0.001**
Funding and Investment	V31	Time of allocation of funding	0.001**
Funding and Investment	V34	Resilience investment with new projects	0.012**
Funding and Investment	V35	Frequency of investing in resilience enhancing activities	0.054*

"*" denotes 90% confidence level, "**" denotes 95% confidence level,

5.6.2. Dimension reduction: Exploratory Factor Analysis

A large number of variables will make it difficult to fit into a model to further explore the relationship among them. Exploratory factor analysis (EFA) is a process to summarize data by grouping the variables into different constructs based on their common variance (Yong and Pearce, 2013). Through factor analysis, multiple observed variables can be combined into one latent variable which was not measured directly. Statistical tool SPSS was used for the calculation.

However, before one can perform factor analysis, it is important to test the data for adequacy and level of correlation.

Two types of tests, namely KMO and Bartlett's test of sphericity were conducted to check the appropriateness of the data and the existence of correlation among variables (Kaiser, 1960; Fadun and Saka, 2018). The KMO value for this dataset was found to be 0.624 which is greater than the cut-off point of 0.5 (Table 5-4). Having a greater KMO value indicates the proper appropriateness of the data for performing EFA. Bartlett's test of sphericity value was <0.001 which is well below the recommended limit of 0.05 indicating that the variables are correlated in some way to perform EFA (Priyanka et al., 2017). The authors recorded the determinant of the correlation matrix and found the determinant value as 0.041which is greater than 0.0001. This indicates that there is no multicollinearity in the data and the data is good to perform factor analysis. 4 components were extracted based on eigenvalue or the amount of variance holds by the components. Total variances for this model are explained in Table 5-4. The first component contributes to the maximum (30.562%) of the variances compared to the other three components. Table 5-4 shows the variables with the loadings. The cutoff point for the variable to be considered in the component is 0.5. Among seventeen significant variables, we have found 11 variables with loadings of more than 0.5. They were divided into four groups constituting four components. The first factor had V8, V4, V7, and V13. The second component had variables V26 and V34. The third component has V16 and V21. The last component has V24, V22, and V5.

Table 5-4 Results of component loadings, KMO, and Bartlett's tests for key components of variables

#	Variables	Components				Factors	Key Components
		1	2	3	4		
V8	Distance of the link/node from the affected area	0.808	-	-	-	F1	Integrated Assets
V4	Number of lanes	0.802	-	-	-		
V7	Having a railroad crossing	0.774	-	-	-		
V13	Ownership of the integrated infrastructure assets	-0.728	-	-	-		
V26	Accessibility to non-machinery resources	-	0.794	-	-	F2	Resource and Investment
V34	Resilience investment with new projects	-	0.771	-	-		
V16	Company employees' knowledge of resilience	-	-	0.719	-	F3	Knowledge
V21	Availability of previous disaster data for the roadway	-	-	0.709	-		
V24	Availability of emergency response equipment	-	-	-	0.872	F4	Response Resources
V22	Access to previous disaster data for the roadway	-	-	-	0.703		
V5	Number of optional routes	-	-	-	0.553		
Rotation sums of squared loadings							
Total variance explained (VE)		3.362	1.554	1.256	1.046		
Percent of variance explained (%)		30.562	14.126	11.418	9.509		
Cumulative percent of VE (%)		30.562	44.688	56.106	65.615		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy							0.624
Bartlett's Test of Sphericity							
Approximate Chi-square				277.127			
Degree of Freedom				55			
Significance				<0.001			
Determinant				0.041			

5.6.3. Base model

For the components developed using variables, four hypotheses were developed based on literature- H1. Integrated assets of the roadway have an impact on rapidity, H2. Resources and investment of the project have an impact on rapidity, H3. Knowledge has an impact on rapidity, and H4. Emergency resources have an impact on rapidity. These hypotheses were introduced to prepare the conceptual model shown in Figure 5-9

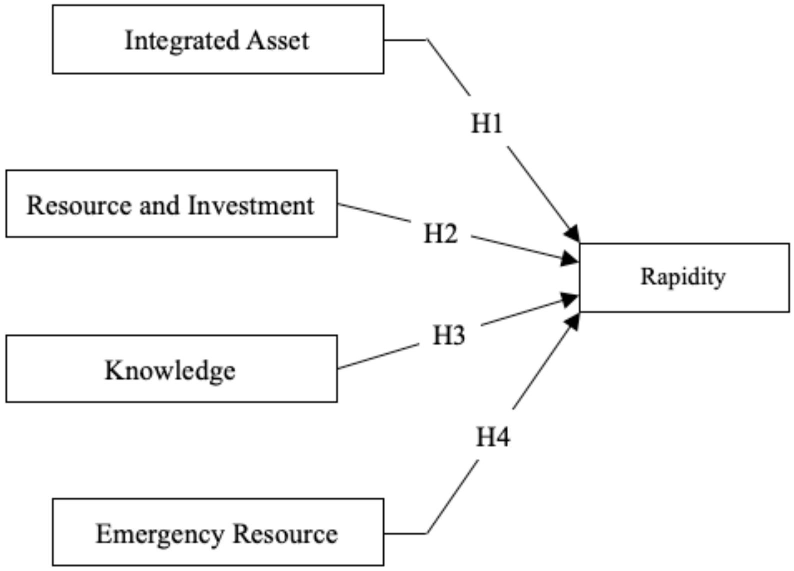


Figure 5-9 Conceptual model

5.6.4. Model Analysis

The models were run for analysis, using SPSS AMOS. Analysis of SEM models follows an incremental approach (Cheng, 2001) that necessitates continuously updating the model, based on the modification indices and the significance of the relationships. Deleting an indicator or even a relationship may become necessary, as modifying one component of a model affects the other parts. Hence, multiple trials must be run that might require removing or adding the same component several times.

Table 5-5 also shows the fit indexes for the model. From that table, χ^2/df was found to be 1.722 (<3), RMSEA was found to be 0.089 (<0.1), CFI was found to be 0.91 (>0.9) and PNFI was found to be 0.51 (>0.5). Such values indicate a good fit for the data to explore the relationships and co-relationships.

Table 5-5 Fit indexes

Fit Indexes	Fit index values	Recommended values (Zaira and Hadikusuma, 2017; Cheng, 2001)
Chi-square (χ^2)	60.258	-
Degree of freedom (df)	35	-
χ^2/df	1.722	<3.00
Absolute fit RMSEA (root mean square residual)	0.089	<0.10
Incremental fit CFI (comparative fit index)	0.91	>0.90
Parsimonious fit PNFI	0.51	>0.50

The model was run for path coefficient and the values are recorded in Table 5-6. The table shows the relationships, the estimate, and the level of significance of the paths. It was found that construct Resources and Investment and knowledge has non-significant relationships with rapidity while all the other paths are statistically significant. It was found from the literature that if a model is well fitted and the parameter has an impact over another parameter, a non-significant parameter should be kept in the model (Schumacker and Lomax, 2004). After consideration of the causal effect of two constructs, the construct region and assets had an impact of 0.58 on the rapidity and the construct resources and funding had an impact of 0.55 on the rapidity. Among the two constructs, construct region and assets has more influence over rapidity.

Table 5-6 Path coefficients of the model

Relationships			Estimate	P
V8	<---	Integrated_Assets	0.523	
V7	<---	Integrated_Assets	0.774	***
V4	<---	Integrated_Assets	0.748	***
V24	<---	Emer_Res	0.607	
V22	<---	Emer_Res	0.561	***
V5	<---	Emer_Res	0.742	***
Rapidity	<---	Integrated_Assets	-0.736	***
Rapidity	<---	Emer_Res	0.413	***
V34	<---	Res_Inv	0.506	
V26	<---	Res_Inv	0.269	0.118
Rapidity	<---	Res_Inv	0.606	0.704
V21	<---	Knowledge	0.533	
V16	<---	Knowledge	0.577	***
Rapidity	<---	Knowledge	0.239	0.787

“Emer_Res” denotes Emergency Resources, and “Res_Inv” denotes Resources and Investment.

5.7. Discussion

Figure 5-10 shows the analyzed model with the path coefficients for each hypothesis.

H1. Integrated assets of the roadway have an impact on rapidity.

The developed model confirmed the first hypothesis that the integrated asset of a roadway has an impact on rapidity. In other words, the presence of integrated assets in a roadway will determine the level of resilience of the network. The authors considered the number of lanes as an asset of the roadway since an increased number of lanes increases the capacity of the roadway. If a damaged roadway has more than one undamaged lane, the lanes can be used as reversible and mobility from both directions could be established given that all the lanes from one direction are damaged (Shaikh et al., 2018). Our model also identifies the benefit of this opportunity and provides a contributing factor of 0.75 as the path coefficient between variable 4 and the latent variable integrated assets. Also, the region of the project is an important measure of vulnerability. To be specific, an infrastructure located near the epicenter of the disaster will suffer the maximum destruction and will require significant recovery time to regain the original level of function (Verma and Gaukler, 2015).

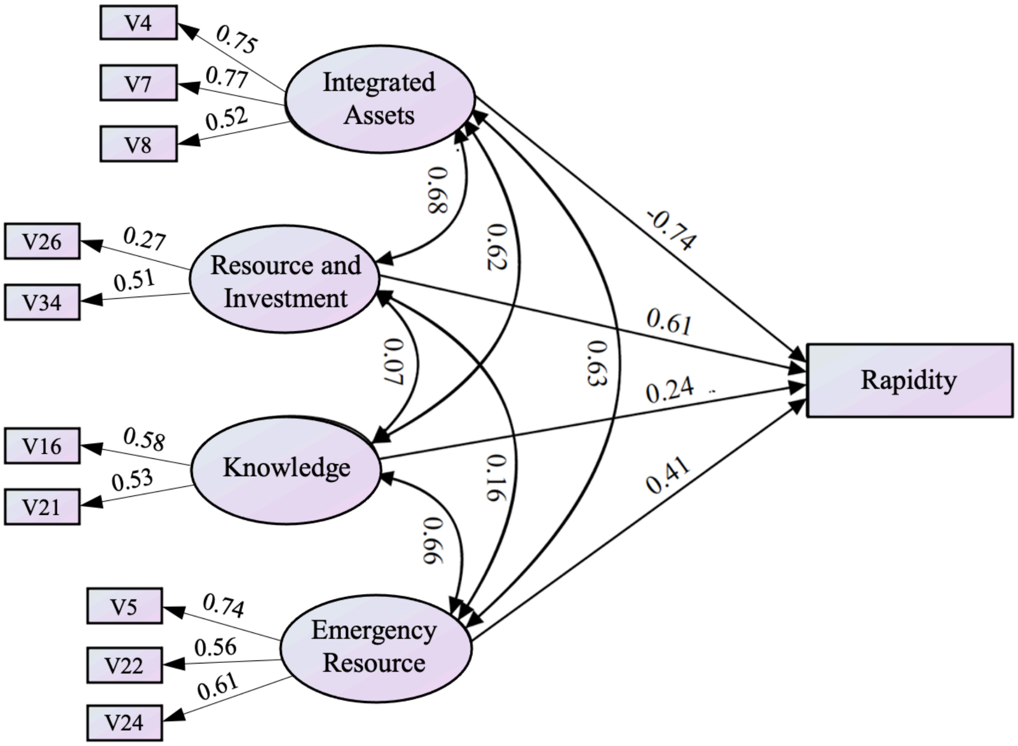


Figure 5-10 Analyzed model with the path coefficient of each hypothetical relationship

H2. Resources and investment of the project have impact on rapidity.

The predictive hypothesis of resources and investment having an impact on the rapidity of the damaged transportation network was not supported by our model. Variable 26 which was accessibility to non-machinery resources has an insignificant contribution to the latent variable resources and investment. However, this construct has a correlation of 0.68 with the construct integrated assets hence it was kept in the model.

H3. Knowledge has impact on rapidity.

The adopted hypothesis that knowledge has an impact on the rapidity of the damaged network was not supported by our model. The latent construct knowledge had an insignificant relationship with the observable variable rapidity with a path coefficient of 0.24. However, the construct knowledge has a high correlation of constructs integrated assets, resource and investment, and emergency resources. Even though the company employees' knowledge on resilience and availability of previous disaster data has insignificant relation with the rapidity of the damaged network, this construct influences the usage of other constructs and influences the level of resilience of the transportation infrastructure indirectly.

H4. Emergency resources have impact on rapidity.

The adopted hypothesis that the emergency resources have an impact on the rapidity of the network was supported by the developed model. Availability of emergency response equipment will highly expedite the emergency response right after a disaster. Proper emergency resources will not only directly expedite the rapidity that is recovery speed but also indirectly boost up the rapidity by reducing the propagation of damage. Similarly, accessibility to disaster data for the roadway will help during the immediate response phase as well as the prolonged recovery phase. Having available optional routes will help in reducing delay by rerouting the traffic from the affected area. This will help in regaining functionality after a disaster hence considered in the construct emergency resources.

5.8. Conclusion

This study aimed to identify the factors that affect the resilience of transportation infrastructures. This study also aimed to develop models to measure the resilience level of the transportation infrastructure. To fulfill the aim of this study a questionnaire was developed which was supported by a comprehensive literature review. The survey was distributed among recipients who have experience in working in different transportation projects under different transportation agencies. After multiple reminder emails, 92 valid responses were collected. Responses were analyzed qualitatively and quantitatively. At this point, 35 variables of resilience measurement were listed and statistical tests were performed to determine the significant variables. To avoid the problem of using too many variables, exploratory factor analysis was performed to identify the components. Based on the concept of structural equation modeling (SEM), a conceptual model was developed using SPSS AMOS for the components identified under for transportation infrastructure projects. The resilience measure rapidity was incorporated into the base model. After multiple trials and errors, final structural model was developed showing all the hypothetical relationships. Model was analyzed and interpreted. Model showed that the most influential factors are integrated assets and emergency resources. Without previous experience in working in reconstruction projects, it is difficult to handle complexities that arise due to existing integrated assets which prolong the recovery activities. Again, without experience in working in the reconstruction project beforehand, it is difficult to utilize the available emergency resources during the immediate response phase of the recovery activities. This difficulty will prolong the recovery activities which indicate lower resilience possession by the network. This study will help the practitioner in addressing the most contributing factors in prolonging the reconstruction activities and develop strategies to handle such delays.

CHAPTER 6

CONCLUSION, LIMITATIONS, AND RECOMMENDATIONS

6.1. Conclusion

This study aimed to identify dimensions to measure the transportation infrastructure resilience from construction and management point of view. After conducting a comprehensive literature review, 20 dimensions were identified which were divided and organized into 35 variables. identified variables were organized into six categories: structural, management, knowledge and exposure, data-related, resources, and funding and investment. Category structural had nine variables collectively which indicate the physical characteristics of the roadway network. The second category is management which has five variables that indicate the condition of the reconstruction works and management system of the authority. The third category is knowledge and exposure which has 6 variables that indicate the level of knowledge of the employees of the management authority. The fourth category data related. This category had three variables that indicate the availability and accessibility of the database related to disaster and resilience activities for a roadway. The fifth category is the resources which included five variables. Collectively these five variables indicate the accessibility and availability of resources. The last category is funding and investment which has seven variables. Collectively they indicate the condition of the funding and investment of the organization.

This study also aimed to determine the variables that are significant in indicating level of resilience of the transportation infrastructures. Keeping that in mind, a survey was developed to identify the impact of each dimension on the level of resilience of transportation infrastructures. The survey was supported by a comprehensive literature review and had 43 questions organized into five sections: demographic-based questions, project-based questions, the concept of resilience-based questions, resilience dimensions-based questions, and best practices related questions. The survey was distributed using electronic media among the potential respondents involved with different state, national, and international transportation agencies, including state departments of transportation (DOTs), the North Central Texas Council of Governments (NCTCOG), the Federal Highway Administration (FHWA), etc. After a couple of reminder emails, 92 valid responses were received. Survey responses were analyzed qualitatively and quantitatively. Qualitative analysis indicated that majority of the participants (60%) had more than 20 years of working experience in positions with high level of authority like directors and supervisors (31%) in different transportation agencies. Moreover, it was found that 73% of the participants had experience in working in at least once in their career in a reconstruction project. collectively, the participants had experience working on simple transportation reconstruction projects with a very limited budget as well as complex projects with a significant budget. Yet, it was found that only 45% of the participants were familiar with the concept of resilience. Data were analyzed quantitatively to determine significant variables form different perspectives. Authors wanted to identify the significant variables that specifically impacts the level of resilience of the complex projects. Keeping that in mind the first set of analysis was performed by grouping the variables based on complexity of the projects and among 35 variables, 16 variables are found to be significant. The second set of analysis were performed based on participants familiarity with the concept of resilience and among 35 variables, 8 variables are found to be significant. Third set of analysis were performed based on the participants involvement in the reconstruction projects and among 35 variables, 17 variables are found to be significant.

This study also aimed to develop a decision-making tool to determine a comparative level of resilience of the transportation infrastructures. For this purpose, Cohen’s d method was utilized to determine the effect size for the variables and based on the effect size, the variables were ranked. The rank-sum method is used to determine the weight of a variable corresponding to a list of ranked variables. A scoring system based on the scale of 1 to 9, 1 being the minimum impact and 9 being the maximum impact was developed. Combining the weights of each variable with the score provided by the users a resilience impact value (RIV) was determined. Accounting all the RIV values for a particular project will provide the resilience level (RL) for the project. In practice, RL value of multiple projects can be determined and a decision on prioritizing critical project for investment and funding in resilience enhancement activities can be made by comparing RL values.

This study also wanted to examine the impact of the significant variables on the resilience measure rapidity. This is to understand the impact of each variable on the reconstruction time and speed, in other words rapidity. A sophisticated modelling technique, structural equation modelling (SEM), was used to develop the model to study the causal relationships of the variables with the rapidity. Before performing modelling, exploratory factor analysis (EFA) was performed to group the variables into different components. Based on literature, the hypothesis was made and introduced into the model in the SPSS AMOS. The model was analyzed, and the results are interpreted. It was the construct integrated assets has the maximum impact on the rapidity of the transportation infrastructures.

Findings of this study will help decision makers in prioritizing the projects based on their criticality in resilience level and support their decisions in investing and funding in most critical transportation infrastructure projects. This study will also help in recognizing critical paths that contribute most to prolonging recovery time and slowing down the recovery speed of a transportation network after a roadway. It will also help practitioners in establishing proper strategies against the corresponding contributing delay factor to improve the resilience of the network.

6.2. Implementation of results in practice

Decision makers and project managers can use the findings of this study in their project to support their decisions of investing and funding to a particular project specially for the projects which are vulnerable to flood and hurricane. They can also find the most contributing factor in elongating recovery time and develop strategies to mitigate the time delay in reconstruction works beforehand.

Based on the models developed (described in Chapter 5) practitioners will be able to identify the critical factors that have impact on the rapidity. Based on the model, Table 6-1 shows the most critical six factors that have impact over the rapidity of the reconstruction works. Factors were ranked from 1 through 6, 1 being the most critical and 6 being least critical.

Table 6-1 Impacts of components on rapidity

Factors	Criticality Rank
Existing railroad crossing	1
Number of lanes	2
Number of optional routes	3
Availability of emergency response equipment	4
Access to previous disaster data for the roadway	5
Distance of the link/node from the affected area	6

Moreover, the outcome of this study is applicable statewide since the data to perform this study was collected from different transportation agencies including ten state DOTs. The decision-making tool can be used by decision-makers, higher level authorities in cities or DOTs, as well as federal or state level resource distributor to prioritize the projects for funding and investment based on their level of resilience. The rapidity model can be used by policymakers and resource distributors to find out most effective strategy to reduce the reconstruction time as well as to enhance resilience level of the transportation infrastructures.

6.3. Limitations

Despite of having multiple benefits, this study possesses couple limitations. First one is that the resilience measurement dimensions were identified through careful review of the literature, however, there might be other factors that rae applicable in construction and reconstruction practice of transportation infrastructures. Second one is that this study relied on the geographical context of the United State of America only.

6.4. Recommended strategies

Based on the survey results and outcomes of this study, the following recommendations are made to manage the critical factors that were identified in this study (Table 6-2).

Table 6-2 Recommended strategies to manage critical factors

Rank	Factors	Suggested Strategy
1	Existing railroad crossing	- Invest in locating integrated assets away from the roadways. - Maintain inter-organizational as well as intra-organizational resilience to avoid conflict while working with different organization responsible for different assets.

2	Number of lanes	- Provide reversible lanes for evacuation routes and/or for vehicles in case of emergency.
3	Availability of emergency response equipment	- Keep an up-to-date inventory of emergency resources, equipment, and spare parts. - Keep consistent communications with responsible personnel about the inventory. - Arrange mock disaster exercises might help in visualizing responsibilities.
4	Number of optional routes	- Perform pre-planning for emergency vehicle access and detour routes during construction and reconstruction. - Designating critical nodes and facilities will facilitate optional routes. - Build out nodes and essential connections early within the staged development of projects.
5	Access to previous disaster data for the roadway	- Maintaining a comprehensive database for disasters and resilience enhancement activities for roadways. - Invest in making the database online and provide access to the responsible personnel.
6	Distance of the link/node from the affected area	- Estimate probable disaster epicenters based on historical data when performing periodical disaster drill.

6.5. Future work

This study can be expanded in multiple ways. This study investigates the impact of variables on the rapidity. Similarly, impact of the variables on other factors like reconstruction cost could be analyzed as well as model developed for rapidity can be expanded considering other factors. Moreover, including experimental studies to validate and justify the developed decision-making tool and the predictive models would be of great improvement.

This study mainly focuses on horizontal transportation system mainly roadway transportation system. Similar studies could be performed for port and harbors, water routes, air routes, airports, bridges etc. Moreover, similar studies can be performed by being specific to a certain type of disaster.

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APPENDIX A

Invitation Letter

Email Subject:

Your Input Needed: Resilience Decision-Making in Critical Infrastructures

Email Content:

Greetings,

You are receiving this letter because we are hoping that you will help us with a very important project. Your expertise and feedback would be valuable as we work to identify and measure the resilience level of critical transportation infrastructures and develop the resilience enhancement strategies. The sponsors of this project are the US Department of Transportation (USDOT) and North Central Texas Council of Governments (NCTCOG).

Your participation is voluntary and your responses to the survey will be kept confidential. If you have any questions or concerns about the study, please feel free to email the Project Principal Investigator, Dr. Sherri Kermanshachi at sharareh.kermanshachi@uta.edu.

We hope that you will take the time to answer the questions by June 30, 2021. Completing the survey should take no longer than 15 minutes. Thank you in advance for your help with this valuable study. To begin the survey, please click on the link below:

https://resiliencedimensionproject2021.questionpro.com/

APPENDIX B

Survey

i. Demographic Information

1. Please specify the organization you work at:
   - ☐ NCTCOG
   - ☐ FHWA
   - ☐ TxDOT
   - ☐ FEMA
   - ☐ Cities/Counties
   - ☐ Private Sector
   - ☐ Other (Please specify: _________________)

2. Which of the following best describes your working experience?
   - ☐ Less than 5 years
   - ☐ 5 to 10 years
   - ☐ 10 to 15 years
   - ☐ 15 to 20 years
   - ☐ 20 to 25 years
   - ☐ More than 25 years

3. What is your job title?
   - ☐ Director
   - ☐ Project Manager
   - ☐ Project Engineer
   - ☐ Field Labor
   - ☐ Other (Please Specify: ____________________)

4. Have you ever involved in the reconstruction of transportation infrastructure?
   - ☐ Yes
   - ☐ No

5. If yes, please mark the most recent type of infrastructure reconstruction you have been involved in.
   - ☐ Roadway
   - ☐ Highway
   - ☐ Bridge
   - ☐ Railway
   - ☐ Airport
   - ☐ Other (Please specify: _____________)
   - ☐ N/A

6. If yes, were you involved in the investment decision making process for that particular project?
   - ☐ Yes
   - ☐ No

7. Are you frequently involved in the investment decision making process for the projects in your organization?
   - ☐ Yes
   - ☐ No

8. Please mention the approximate value of the most recent reconstruction project you/your company have worked on.
   - ☐ Less than 1M
   - ☐ 1M-5M
   - ☐ 6M-10M
   - ☐ 11M-15M
   - ☐ 16M-20M
   - ☐ More than 20M

ii. Resilience Concept

9. How familiar are you with the concept of “*resilience*” and “*build back better*”?
   - ☐ Not at all familiar
   - ☐ Slightly familiar
   - ☐ Somewhat familiar
   - ☐ Moderately familiar
   - ☐ Very familiar

10. How agree are you with the statement “*improving resilience is better than investing in recovery*?”
    - ☐ Not at all agree
    - ☐ Slightly agree
    - ☐ Somewhat agree
    - ☐ Moderately agree
    - ☐ Agree

11. Would you say project decision-making and analysis of needs for infrastructure maintenance also includes resilience considerations on a frequent and consistent basis?
    - ☐ Not at all agree

☐ Slightly agree
☐ Somewhat agree
☐ Moderately agree
☐ Agree

12. How does your agency distribute annual funding between new projects and resilience enhancement activities?

New Projects: _____%

Resilience Enhancement: _____%

13. Please rate the importance of the identified factors on the pace of the recovery process?

	Not at all important 1	Slightly Important 2	Somewhat Important 3	Moderately Important 4	Very Important 5	Quite Important 6	Extremely Important 7
Average lost household income							
Average lost businesses							
Damage to major infrastructure systems, such as roadway networks, bridges, etc.							
Damage to medical services like hospitals							
Damage to residential housing							
Environmental contamination, such as reduced water and air quality							

14. In your organization, are resilience and vulnerability considered as part of the investment decision making and prioritization processes?
☐ Yes

☐ No

15. Does your organization measure and/or quantify the resilience of infrastructures under their authority?
    ☐ Yes
    ☐ No

16. If yes, how does your organization determine the resilience level of the existing infrastructures?
    ☐ Quantitative Assessment
    ☐ Qualitative Assessment
    ☐ Mixture of Quantitative and Qualitative Assessments

17. If yes, what tools/techniques are used in measuring the resilience level of the infrastructure?
    Answer: ____________

18. How does your organization compare and prioritize the resiliency enhancement projects?
    Answer: ____________

19. Does your agency have a database of historical resilience enhancement activities and their associated costs?
    ☐ Yes
    ☐ No

iii. Resilience Dimensions

20. Please determine how agree are you with the statements based on transportation infrastructure reconstruction projects you were involved in:

	Not at all Agree 1	Slightly Agree 2	Somewhat Agree 3	Moderately Agree 4	Very Agree 5	Quite Agree 6	Extremely Agree 7
Node disruptions cause more delays compared to link disruptions of the same damage severity.							

The total length of disrupted roadways determines serviceability delays.
Resilience and efficiency are not necessarily correlated.
Unavailability of emergency response equipment such as snow or debris removal equipment can significantly delay the reconstruction process.
It is more difficult to reroute traffic when the affected component is the node compared to when the affected component is the roadway.
Not having the right information at the right time made the recovery process more difficult.
Rerouting traffic becomes difficult when the distance between two consecutive nodes on a network is relatively large.
Having additional lanes to turn a one-way roadway into a two-way roadway will make the rerouting of the traffic more convenient in case of emergency.
Links/nodes far away from the affected area will have fewer traffic disruptions.
Previous experience of managing a network during disastrous events accelerate the recovery process.
Having a railroad crossing on the affected roadway

delays the reconstruction work.

21. When does your organization consider allocating funding to resilience enhancement activities and projects?
    - ☐ The allocation of funding to resilience enhancement activities are performed on the regular basis.
    - ☐ The allocation of funding to resilience enhancement activities are usually considered after occurrence of a disaster.

22. While designing and planning a transportation network, does your organization consider the availability of the emergency resources required in case of reconstruction due to a disastrous event?
    - ☐ Yes
    - ☐ No

23. While designing and planning a transportation network, does your company consider the accessibility of the emergency resources required in case of reconstruction due to a disastrous event?
    - ☐ Yes
    - ☐ No

24. How difficult is to access data from previous disruptive events for a particular roadway?
    - ☐ Not at all difficult
    - ☐ Slightly difficult
    - ☐ Somewhat difficult
    - ☐ Moderately difficult
    - ☐ Very difficult

25. How helpful would be accessing data from previous events for a particular roadway in the decision-making process for the recovery of that roadway after a new disruptive event?
    - ☐ Not at all helpful
    - ☐ Slightly helpful
    - ☐ Somewhat helpful
    - ☐ Moderately helpful
    - ☐ Very helpful

26. Does different ownership of railroad crossings, intersecting roadways, and/or any integrated infrastructure assets (signals, intelligent transportation system apparatus, utility conduits, etc.) delay the recovery activities?
    - ☐ Yes
    - ☐ No
    - i. If yes, how? _________________
    - ii. If yes, which one cause higher delay in recovery? ________________

iv. Resilience Enhancement Best Practices

27. Please determine how agree are you with the suggested best practices aiming to increase the resilience of transportation networks:

	Not at all Agree 1	Slightly Agree 2	Somewhat Agree 3	Moderately Agree 4	Very Agree 5	Quite Agree 6	Extremely Agree 7
With the increased number of nodes, the resilience of a network decreases.							
When disrupted, long links will require additional paths for functionality. Having more connections between roadways will increase resilience.							
A project manager with proper knowledge about stored emergency equipment can increase resilience.							
With the number of available optional routes, resilience will increase.							
With the number of available lane numbers, the resilience will increase.							

Having a disaster database will help significantly with the disaster prevention enforcement plans and to cope with disaster consequences.	
Ensuring the availability of resources for emergency reconstruction during the planning process of the networks will increase the resilience of that network.	
Ensuring access to the emergency resources during the planning process of the networks will increase the resilience of that network.	
Periodical review of storage and accessibility of the emergency resources will increase resilience.	
Taking extra care of the emergency nodes (including critical emergency response facilities such as fire stations and hospitals) will improve the resiliency of the system.	

28. Based on your experience and understanding, please list top best practices adopted by your organization to improve the resilience of the transportation networks.

Answer: __________

v. Project-based Resilience Questions

To answer the questions in this section, please select a **reconstruction project** of a transportation infrastructure that was damaged due to a disaster and you/your agency were/was involved. To select a project, please consider the following requirements:

a. Reconstruction of transportation infrastructures due to any disaster is acceptable; and
b. Reconstruction of any type of transportation infrastructure is acceptable (Highway, bridge, roadway, tunnel, etc.)

29. What type of disaster was the cause of damages to the selected reconstruction project?
    - ☐ Cyclone
    - ☐ Hurricane
    - ☐ Flood
    - ☐ Thunderstorm
    - ☐ Tornado
    - ☐ Wildfires
    - ☐ Earthquake
    - ☐ Extreme Heat/Cold
    - ☐ Other (Please specify: __________)

30. In what year did the selected disaster happen?
    Answer: _______________

31. Approximately how many extra reconstruction projects were defined to address the damages due to this disaster?
    - ☐ Less than 5 projects
    - ☐ Between 5-15 projects
    - ☐ Between 15-50 projects
    - ☐ Between 50-100 projects
    - ☐ Over 100 Projects

32. What was the type of the selected reconstruction project which you were involved in?
    - ☐ Roadway
    - ☐ Node
    - ☐ Roadway network including node
    - ☐ Railway crossing
    - ☐ Airport
    - ☐ Other (Please specify: ______________)

33. What was the role of your organization in this reconstruction project?
    - ☐ Owner
    - ☐ Contractor
    - ☐ Engineer/Designer

☐ Subcontractor
☐ Other (Please specify: ______________)

34. What was the level of damages in the selected reconstruction project compared to its pre-disaster condition?
    ☐ Less than 10%
    ☐ Between 10% to 25%
    ☐ Between 25% to 50%
    ☐ Between 50% to 75%
    ☐ Between 75% to 100%

35. What was the approximate cost of this reconstruction project?
    Reconstruction Project Cost (in Thousands): __________________

36. What was the approximate duration of this reconstruction project?
    Reconstruction Project Duration (in Months): __________________

37. Did your organization face any challenges in acquiring the funding needed for this reconstruction project?
    ☐ Yes
    ☐ No

38. How long after the disaster was this reconstruction project initiated?
    ☐ Less than 2 weeks
    ☐ Between 2 weeks and 1 month
    ☐ Between 1 month and 2 months
    ☐ Between 2 months and six months
    ☐ Between six months and 1 year
    ☐ More than 1 year

39. Please rate the complexity level of the selected reconstruction project.
    ☐ Slightly complex
    ☐ Moderately complex
    ☐ Highly Complex

40. How remote (distance from highly populated areas) was this reconstruction project located?
    ☐ Less than 5 miles
    ☐ 5-15 miles
    ☐ 15-25 miles
    ☐ 25-50 miles

☐ More than 50 miles

41. Please rate the shortage of human resources in the selected reconstruction project.
    - ☐ No shortage
    - ☐ Slight shortage
    - ☐ Somewhat shortage
    - ☐ Moderate shortage
    - ☐ Severe shortage

42. Please rate the shortage of <u>material resources</u> in the selected reconstruction project.
    - ☐ No shortage
    - ☐ Slight shortage
    - ☐ Somewhat shortage
    - ☐ Moderate shortage
    - ☐ Severe shortage

43. Please provide the following information in order to recognize the relative improvement of the affected area due to reconstruction.

	Before reconstruction	After reconstruction
Number of lanes		
Number of nodes		
Number of arteries in a node		
Length of the roadway		