Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Development of a Multi-Level Dynamic Model to Measure the Resilience Level of Transportation Infrastructure Networks

Project No. 20ITSUTA27

Lead University: The University of Texas at Arlington

Final Report

August 2021

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

Acknowledgements

The authors wish to acknowledge the sponsorship of the North Central Texas Council of Governments through its University Partnership Program, the U.S. Department of Transportation, and Federal Highway Administration. In particular, the directions, guidance and insights offered by Mr. Jeffery Neal is greatly appreciated.

TECHNICAL DOCUMENTATION PAGE

1. Project No.	2. Government Accession No.	3. Recipient's Catalog No.
20ITSUTA27		

4. Title and Subtitle	5. Report Date
Development of a Multi-Level Dynamic Model to Measure the Resilience Level of Transportation Infrastructure Networks	August 2021
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
PI: Sharareh Kermanshachi; Jianling Li; Thahomina Jahan Nipa	
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Transportation Consortium of South-Central States (Tran-SET) University Transportation Center for Region 6 3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803	**11. Contract or Grant No.**
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
United States of America Department of Transportation Research and Innovative Technology Administration	Final Research Report August 2020 – August 2021
	14. Sponsoring Agency Code

15. Supplementary Notes

Report uploaded and accessible at Tran-SET's website (http://transet.lsu.edu/).

16. Abstract

The recent increase in disasters is making the largest critical infrastructure system namely the transportation infrastructure system susceptible to unexpected damage. Discontinuation of services provided by transportation infrastructures will create significant societal, economic, and collateral damages. Therefore, this study aims to identify dimensions to measure the resilience of the transportation infrastructures. This study also aims to develop a model to measure the resilience of the transportation infrastructures resilience. 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. Statistically significant variables were used to develop a resilience measurement tool. The developed tool will provide relative resilience measures for multiple projects which will help in identifying the most vulnerable segment of the transportation infrastructure network. Exploratory factor analysis (EFA) was performed to identify the constructs and structural equation modeling (SEM) was used to develop the model. Without previous experience in reconstruction works, handling integrated assets becomes very critical. Also, such inexperience makes it difficult to handle emergency resources properly. However, such issues regarding integrated assets can be resolved by investing in locating integrated assets away from the roadways, so if a break in a railroad crossing or utility line occurs or emergency repairs are needed, the impact on the roadway operations can be minimized. To avoid issues related to access to previous disaster data for the roadway this study suggess investing in preparing an interactive online platform for recording and reviewing data related to disasters as well as previous resilience enhancing activities for the roadway with easy access credentials. The findings of this study will support practitioners and decision-makers in investing in the appropriate resilience enhancement activity project for funding and investment.

17. Key Words	18. Distribution Statement
Transportation Infrastructures; Resilience; Reconstruction; Model; Resilience Measurement	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	73	

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

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

EXECUTIVE SUMMARY

The advancement of human civilization depends on the proper functioning of critical infrastructures (CIs) like power supplies, water supplies, transportation infrastructures, etc. The transportation infrastructure serves as a lifeline after a disaster since the evacuation of residents and rendering of primary care services depend on it. Damaged transportation structures hamper the mobility of people in the affected area and increase the monetary loss caused by the disaster by prolonging the recovery of the affected community. The resources required to perform reconstruction activities are provided by either public assistance, government agencies, or insurance companies, and are limited; therefore, before allocating them, decision-makers have to be cognizant of resilience measuring dimensions. This study aims to determine the dimensions for measuring the resilience of the transportation infrastructure while developing a model that reflects the relationships between them.

A comprehensive literature review was conducted to develop a list of potential resilience measuring dimensions, and a survey was developed, based on that list. The survey was distributed electronically, and after multiple follow-up emails, 92 valid responses were collected and analyzed qualitatively and quantitatively. Approximately 73% of the participants had been involved in at least one reconstruction project during their career and 60% had worked for transportation infrastructure agencies for more than 20 years. Only 45% of the participants were familiar with the concept of resilience.

A list of 35 potential variables was developed, and statistical tests were performed to identify statistically significant variables. Using Cohen's d method, the effect size of the variables was determined. The rank-sum method was utilized to assign weight to the variables. Weighted variables were used to develop a tool to quantify the resilience of the transportation infrastructures. The developed tool will provide relative resilience to the transportation infrastructure projects. Using this tool, a comparative analysis among multiple projects can be performed and the most vulnerable transportation infrastructure segment can be identified. This will help decision-makers to make their investment decisions on resilience enhancement activities based on the vulnerability of the segment of the transportation infrastructures.

Moreover, the model was developed using the structural equation modeling (SEM) technique to identify the relationships among different factors and resilience measures. Without previous experience in reconstruction works, handling integrated assets becomes very critical. Also, such inexperience makes it difficult to handle emergency resources properly. However, issues related to integrated assets, one must try investing in locating integrated assets away from the roadways, so if a break in a railroad crossing or utility line occurs or emergency repairs are needed, the impact on the roadway operations can be minimized.

1. INTRODUCTION

1.1. Background

Human beings are dependent on critical infrastructures (CI's), and transportation infrastructures are among the most vulnerable to unpredictable and destructive natural disasters *(1, 2)*. In 2011, Hurricane Irene hit the East Coast of the U.S, damaging more than 500 miles of highways, 2000 miles of roadways, and 200 miles of railways, resulting in 56 deaths and approximately $15.6 billion in losses *(3)*. Hurricane Harvey in 2017 caused the destruction of houses and infrastructures worth $190 billion in the Texas and Louisiana region *(4, 5)*. A great monetary price is paid if the recovery of transportation infrastructures is delayed *(6),* as their condition is highly instrumental in determining the recovery pace of other sectors, including residential buildings and industrial plants *(7)*. However, the recovery phase is extra critical due to the chaotic nature of the post-disaster environment *(8, 9)*. On the other hand, a resilient system not only reduces the probability of the system failing but also reduces the amount of destruction caused by the disaster and the amount of time required for reconstruction *(10, 11)*.

The adverse impacts of natural disasters become astounding when infrastructures are not resilient *(12)*. Resilience is a term that has been studied for more than half a century, first by ecologists and eventually by almost all the other application domains *(13)*. Hence, several definitions of resilience exist in the literature *(14)*, but in a nutshell, the resilience of a system is its ability to bounce back to its predetermined level of performance within the shortest possible time. 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 required to achieve that level *(15)*. A resilient 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 person responsible for the decision-making process, economic resilience indicates the availability of monetary resources for recovering from the disaster, and 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 *(16)*. This study mainly focuses on the technical resilience aspect. According to Wan et al. *(3),* current literature does not provide a standard definition of resilience for transportation systems. For the purpose of this study, however, the resilience of transportation infrastructures is 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.

1.2. Problem Statement

Over the last few decades, resilience has been studied vigorously to assess damages and performance of infrastructures that suffered from disturbing events like natural and/or man-made hazards *(17)*. Researchers, governments, and agencies are interested in infrastructure resilience *(18)*. Critical infrastructure resilience is a major objective that has been carried out by The Department of Homeland Security (DHS) for more than a decade *(19)*. The significant task under this objective is to encourage agencies to make an effort to measure the resiliency of infrastructures to reduce risks and the possibility of damage by expanding the capacity of the system *(20)*. Unfortunately, transportation resilience wasn't considered an independent focus of study until 2009 (3); consequently, many models and frameworks related to transportation resilience had already been developed. For example, Faturechi and Miller-Hooks *(20)* developed four mathematical formulations in the context of transportation networks that focused on functionality, rapidity, recovery, and flexibility of resilient systems, and Freckleton et al. *(21)* developed a conceptual framework considering only the level of damage redundancy, and rapidity of resilience. However, a comprehensive model that considers all the dimensions of resiliency by measuring the organizational, economic, technical, and social aspects of transportation systems is yet to be developed *(1)*.

2. OBJECTIVES

This study aims to develop tool that measures the comparative resilience level of existing transportation infrastructures and suggests strategies to improve it. It identifies technologies that could increase the resilience level of infrastructure projects, reducing the probability of failures due to extreme weather catastrophes. To fulfill the aim of this project, the following objectives were formulated:

- Identify the resilience dimensions of transportation infrastructures.
- Develop a resilience measurement tool.
- Develop a model showing causal relationships of dimensions of resilience with the resilience of transportation infrastructure networks.
- Establish resilience enhancement strategies for transportation infrastructures.

3. LITERATURE REVIEW

3.1. Disaster Management

Both the rate of occurrence and intensity of the destruction of man-made, as well as natural disasters, have increased to a concerning level in recent years *(22-25)*. Because of their age and vulnerability, active and complex critical infrastructures (CIs) such as transportation, communication, energy, water, etc. are facing more challenges than ever before as they attempt to continue functioning under the impact of disasters *(26,27)*. Moreover, technological advancement is making construction as well as reconstruction projects even more complex and risky *(28)*. Destruction of transportation infrastructure not only causes the direct cost of reconstruction but also causes indirect cost due to loss of mobility *(10,29)*. Compromised transportation infrastructures also cause safety issues for community people *(30)*. The recovery of the affected community also depends on the recovery of the transportation infrastructures *(31, 32)* as well as the recovery of the emergency response system (33). The interdependency characteristic of a transportation network amplifies its susceptibility to damage from a disaster, as the system must undergo four phases: mitigation, preparedness, response, and recovery. The mitigation and preparedness phases occur before the disaster hits; hence the impacts only can be projected; however, they are the foundation for a timely and effective recovery *(34-36)*. The response phase lasts until immediately after the disaster; however, the recovery is a complex phase that extends until the damage has been repaired or reconstructed and the affected community has returned to life as it was before the disaster *(37)*. Decisions that are made during the mitigating and preparedness phases highly impact the time and effectiveness of the response and recovery phases *(38)*. Throughout the literature, resilience and robustness are mentioned as the most effective preparedness actions for reducing the cost and schedule of the recovery phase *(20)*. Moreover, policymakers as well as practitioners always prioritize the fastest recovery and a resilient system ensures this requirement *(39, 40)*. The recovery phase also provides the opportunity to build back better which eventually enhances the resilience of the infrastructure *(41, 42)*.

Massive destruction with significant economic losses wreaked by disasters like Hurricane Katrina, Hurricane Sandy, etc. has occurred in the US *(43, 44)*. This has forced the US to change its priority from risk-based management to resilience-based management. The risk-based management system focused on the likelihood of occurrence and level of impact of disasters, whereas resilience-based management focuses on integrating measures to improve the inherent capability of the system and to provide continuous functionality, even after a disaster *(20)*. Such a shift of management is necessary for all civil infrastructures, but especially for transportation infrastructures *(45),* because the transportation infrastructure’s discontinued service will remarkably increase the indirect cost of the disaster. Moreover, timely recovery highly depends on the recovery of transportation infrastructures *(46)*. To ensure and sustain continuous function, constant investment is made in transportation infrastructures. Incorporating the concept of resilience in every phase of the disaster for transportation infrastructures will greatly reduce the amount of economic loss, as well as the cost of recovery.

3.2. Concept of Resilience

The concept of resilience has been studied for more than five decades – since 1973, when the renowned ecologist, Holling, first conceptualized it with respect to ecological systems *(47)*. Over the years, many sectors, including infrastructures, communities, health agencies, etc. have incorporated the concept of resilience into their respective studies and defined it accordingly *(13, 48, 49)*. Hence, the current literature provides a significant number of definitions of resilience for each field of study *(14, 50)*. Dick et al. *(51)* defined the resilience of critical infrastructure as the inherent ability to reduce the negative impact of a disaster by establishing alternative activities and developing emergency responses. Lam et al. *(52)* provided a straightforward definition of resilience when they claimed that the ability of a community to recover from the damages that occur due to a disaster is the resilience of that community. Several other definitions are listed in Table 1.

Table 1. Definition of Resilience

Reference	Field of study	Definition
(53)	Railway	Ability to be flexible and to have an acceptable level of deviation from the performance due to disaster
(54)	Supply chain	Ability to keep providing for the customer by resisting, adjusting, and recovering from a disaster
(55)	Road network	Ability to absorb, adapt, and recover from a disaster by implementing emergency traffic management and evacuation routes
(1)	Transportation	Having inherent characteristics to minimize the impact of disasters by coping with immediate recovery activities
(56)	Societal	Ability to recover after a disaster to transform into a new state of steady operation
(57)	Industry	Ability to absorb the impact of disasters by introducing diversity into the system
(58)	Interorganizational	Ability to reduce the impact of risk by adopting effective collaboration to execute common disaster response
(59)	Ecological	Ability to bounce forward into a new balanced state after a disaster
(60)	System	Adaptive ability to rapid recovery from disruptive events to ensure continuous performance
(19)	Critical Infrastructure	Ability to gain a predefined level of functionality within the least amount of time after a disaster

The concept of resilience also can be explained by considering the static component, performance, as a function of the dynamic component, recovery time, for a system *(15)*. Figure 1 shows a system's performance level against time, including a disastrous event. Here, the Y-axis identifies the level of performance, and the X-axis identifies the time. A system with a good resilience capability will experience the minimum amount of loss from disruptions (minimal difference between p_t and p_0) and will have a faster recovery (difference between t_2 and t_3 will be reasonable).

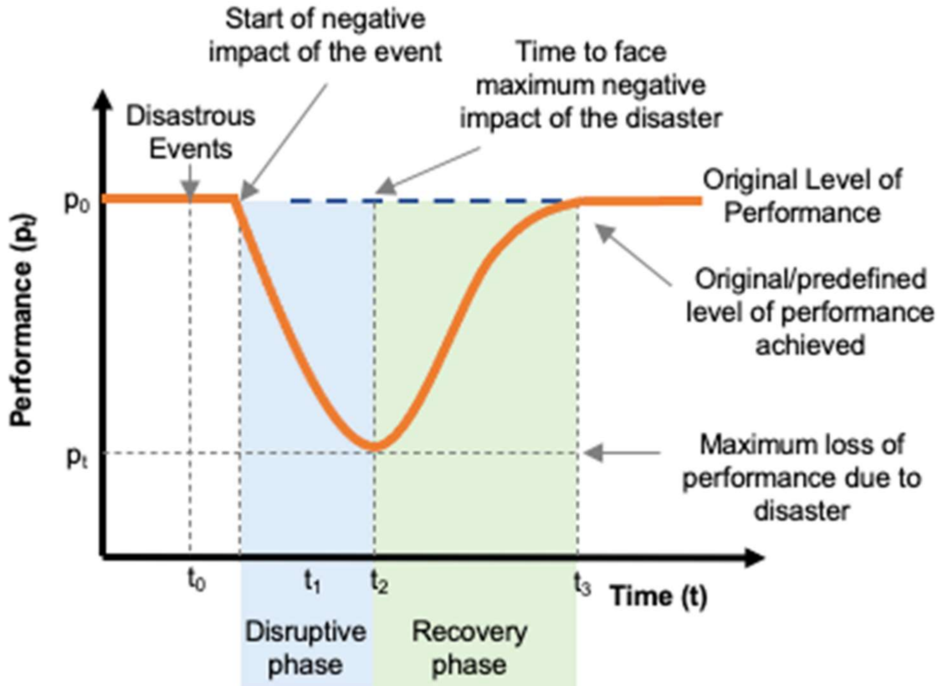


Figure 1. Resilience concept

Throughout literature, researchers use numerous terminologies to define and interpret the concept of resilience *(61)*. In engineering research, the level of functionality was identified as robustness and the recovery time was identified as rapidity by McDaniels *(62)*. The terms robustness, rapidity, redundancy, and resourcefulness were also used by Zhang et al. *(63)* to define road-bridge networks. These four terminologies, which are commonly known as 4R, are the most commonly used in resilience research, irrespective of the field of study. Many researchers *(64, 65)* used 4R in their studies. With time, however, the usage of resilience has broadened into many sectors, and many more terminologies have been identified and adopted, based on the usage of the concept *(66)*. For example, mobility, which indicates a network's ability to move vehicles or people from one place to another, is an important component of transportation infrastructure resilience. A comprehensive list of such terminologies and an explanation of them are shown in Table 2.

Table 2. Terminologies Used in the Research of Concept of Resilience

#	Term	Description	Frequency
1	Robustness	Ability to withstand a certain level of loss of functionality due to disaster	15
2	Redundancy	Having components that will continue to perform even under disastrous events	15
3	Resourcefulness	Having emergency resources available for recovery, including materials and personnel	15
4	Rapidity	Time to recover to the original or a predefined level of functionality after a disaster	15

5	Preparedness	Ability to take measures to withstand a disaster before it occurs	10
6	Mobility	Ability to move vehicles or people from one place to another	8
7	Responsiveness	Ability to link recovery activities with a crisis	5
8	Quality	Interpretation of the level of performance of an affected system before it is affected by a disaster	5
9	Fragility	Calculative risk for a system to endure a particular level of disaster	5
10	Adaptability	The ability of the system to efficiently utilize lessons learned from previous disaster experiences	5
11	Collaboration	Systematically sharing information and resources within components and among stakeholders	5
12	Optimization	Ability to get the most out of the available resources	4
13	Vulnerability	Systems' exposure to the disruptive event	4
14	Sustainability	Capacity to tolerate the negative impacts of a disaster	4
15	Diversity	Having a broad range of components with different functionalities to endure different threats	4
16	Safety	Ability to protect users from the risk of hazards	4
17	Efficiency	Ability to produce a larger outcome compared to providing input	3
18	Autonomous components	Having the ability to function independently	3
19	Strength	The capability of facing a disruptive event without creating a significant crisis	3
20	Interdependent	Ability of the system's components to support each other	3
21	Resistance	Ability to resist the first impact of a disaster	3
22	Survivability	Ability to lessen vulnerability	3
23	Reliability	Ability to withstand a wide range of disasters	2
24	Response and Recovery	Combination of resourcefulness and rapidity to gain back performance after a disaster	2

3.3. Dimensions of Transportation Resilience

The transportation sector began conducting independent studies on the concept of resilience in 2009. Since then, the subject has rapidly gained in popularity, and the current literature contains a significant number of related studies. Many researchers have used different definitions of resilience and different dimensions for measuring the resilience of transportation infrastructures *(1, 67, 68)*. The authors have found that the dimensions that are currently being used most often throughout the literature measure the absorptive, adaptive, and restorative capacity of transportation infrastructures (Figure 2). A transportation system with the necessary level of redundancy, efficiency, diversity, strength, adaptability, autonomous components, collaboration, mobility, safety, and rapidity can be called technically, organizationally, socially, and economically resilient.

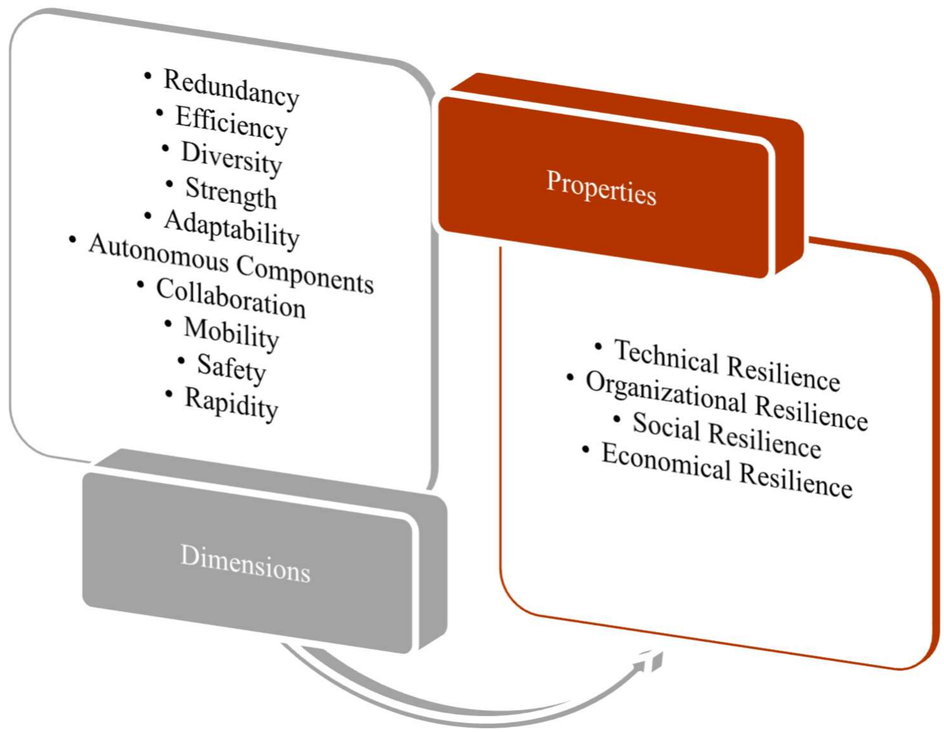


Figure 2. Dimensions to Measure Resilience of Transportation Infrastructures, Based on Current Literature

3.4. Summary

Despite the term "resilience" being rich with numerous definitions and dimensions, the current literature does not provide a universal definition in relation to transportation infrastructures. For the purpose of this study, the resilience of transportation infrastructures is defined as the ability to tolerate disturbance while keeping the basic structure and function intact and to recover from performance deviation after the disaster within a reasonable timetable and budget.

A significant number of dimensions exist throughout the literature for measuring and quantifying resilience, yet they are not adequate for interpreting the resilience level of transportation infrastructures. The majority of these dimensions do not have a fixed meaning and countable measure; instead, they are defined and quantified based on the scope of the study. In addition, the same terminology is defined in different ways throughout the literature. Hence it is a prerequisite to prepare a list of resilience-measuring variables to quantify the level of resilience of the physical segment of transportation networks.

4. METHODOLOGY

This study followed a five-step methodology that is shown in Figure 3. Step 1 is the literature review, step 2 is the database analysis, step 3 is the data collection, step 4 is the data analysis, and step 5 is model development. In the first step, the team focused on collecting related articles to understand the current condition of the literature related to resilience study. In the second step, the collected articles were analyzed, and a list of potential variables was prepared. In the third step, a survey was developed to collect data for this study. In the fourth step, collected data were analyzed demographically and statistically. In the fifth step, a resilience measurement model was developed and validated. At the end of this step, strategies to handle most contributing factors to prolong recovery activities were proposed.

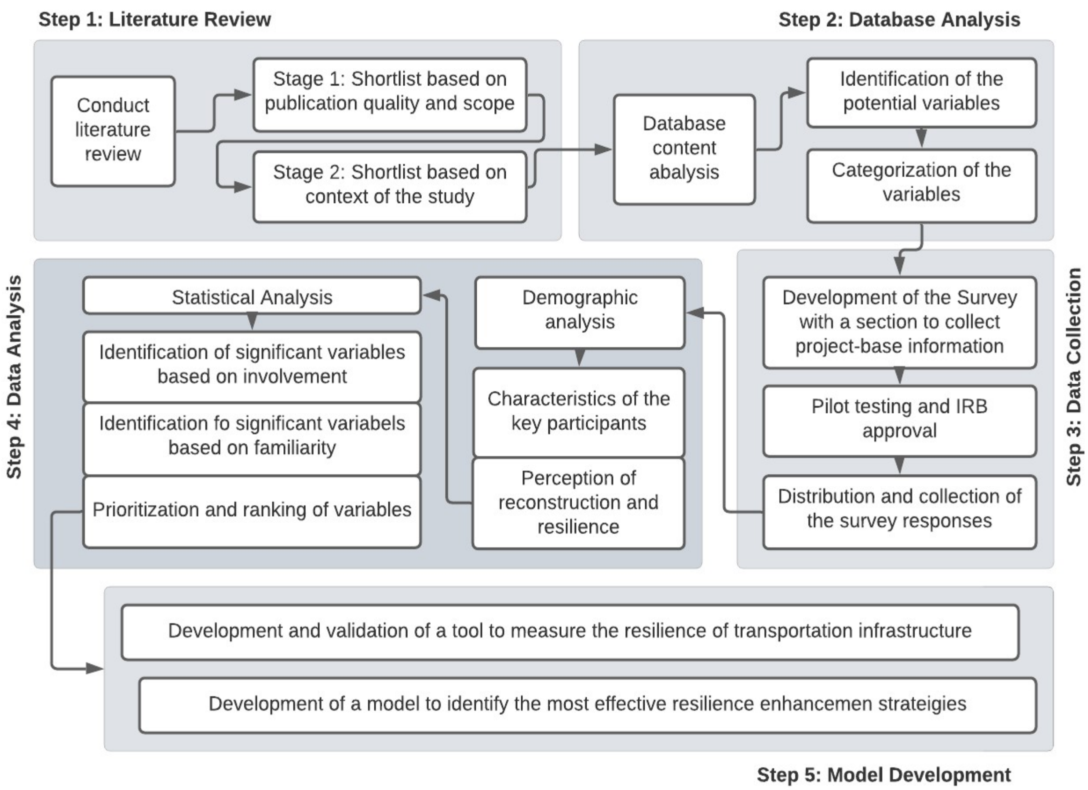


Figure 3. Project Flow Diagram

4.1. Literature Collection Process

A keyword search option was used to collect reliable 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 were entered into 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-reviewed sources and articles that were published from the year 2000 to the current time were given priority. The initial search resulted in 600 articles; however, after considering their relevance to the scope of the project, only 372 articles were shortlisted for content analysis.

4.2. Content Analysis

Content analysis was performed in two stages. The first stage aimed to understand the current literature as it pertains to the current research trend of resilience. During this stage, articles were categorized based on their publication year, number of citations, discipline, geographic location, and disaster type. Information regarding the concept of resilience, including adopted definitions, characteristics, and dimensions, was collected, and data analysis was prepared. Table 3 shows the list of collected information.

Table 3. Information Collected for Preparing the Database

Stages	Collected Information
1st stage scrutinization	- Publication year - Number of citations - Discipline - Geographic location - Disaster type - Adopted/proposed definition of resilience - Explained characteristics of resilience - Adopted/proposed dimensions of resilience
2nd stage scrutinization	- Definition of resilience with respect to the field of transportation infrastructure - Characteristics of resilience with respect to characteristics of field of transportation infrastructure - Dimensions of resilience with respect to field of transportation infrastructure - Other related information

The second stage of content analysis was performed for 109 articles that were related to the transportation discipline and mainly discussed the concept of resilience with respect to transportation engineering. After thoroughly reviewing each article, the authors were able to identify the major characteristics of transportation infrastructure resilience.

4.3. List of Potential Dimensions

The content analysis resulted in dimensions that might be able to indicate the transportation infrastructure's level of resilience. Since the focus of this study is primarily to determine the level of resilience of a roadway network, the 20 best-suited potential dimensions were listed. Table 4 shows the dimensions that could potentially affect the resilience of a roadway segment and provides a description of each.

Table 4. Potential Dimensions Affecting Resilience of a Roadway Segment

#	Dimensions	Description	Reference
1	Node number	A damaged node (intersection) that affects the mobility of the network	(63, 69)
2	Link length	Rerouting from a longer link will be comparatively more difficult.	(69)
3	Disruption length	A longer disruption length of a link will require more time and resources from which to recover.	*(69)*
4	Delay	Time to move from one place to another after a disaster when there are more vehicles than normal due to the disaster	*(69)*
5	Investment type	Traditional investment focusing on immediate delay lessening activities only will make the network vulnerable to network against sudden disasters	*(1)*
6	Optional route numbers	A greater number of optional routes will enhance the resilience of a network by increasing the redundancy of the network.	*(70)*
7	Accessibility of resources	Planned and predefined access to resources will expedite recovery speed after a disaster.	*(3)*
8	Resources storage	Storing resources for emergency response and recovery will ease the recovery process.	*(71)*
9	Disaster experience	Personnel's previous experience in working in similar situations will increase the efficiency of a recovery operation.	*(3)*
10	Organizational process	A strong intra-organizational process will increase the crisis-handling capacity of organizations.	*(1)*
11	Information dissemination	Having the right information at the right time will facilitate prompt decision-making during pre- and post-disaster activities.	*(1)*
12	Disaster database	A disaster database helps in the planning phase of disaster recovery.	*(72)*
13	Availability of budget	The availability of an emergency budget will increase the speed of the response and recovery phases of a disaster.	*(1)*
14	Preparedness actions	Preparedness actions will lower the cost and time of corresponding recovery actions.	*(3)*
15	Distance from the epicenter	Impacts of disaster lessen with the increase of distance from the epicenter of the disaster.	*(73)*
16	Lane number	Having multiple lanes creates the potential opportunity to use an undamaged lane as a reversible lane to restoring mobility from both directions immediately after a disaster.	*(65)*

17	Learning from historical data	Historical data of a roadway will help in predicting its potential risk and vulnerability.	*(74)*
18	Emergency response equipment	Emergency response equipment is required to perform response and rescue activities immediately after a disaster.	*(71)*
19	Resource allocation	Allocation of resources for resilience enhancement activities increases the absorptive, adaptive, and restorative capabilities of the network.	*(1)*
20	Emergency nodes	Nodes with fire stations, hospitals, etc. should be given extra care to make the whole network resilient.	*(63)*

The dimensions were studied and elaborated into 36 variables to better understand their impact on the level of resilience of transportation infrastructures. The identified variables were placed into six categories, as shown in Figure 4.

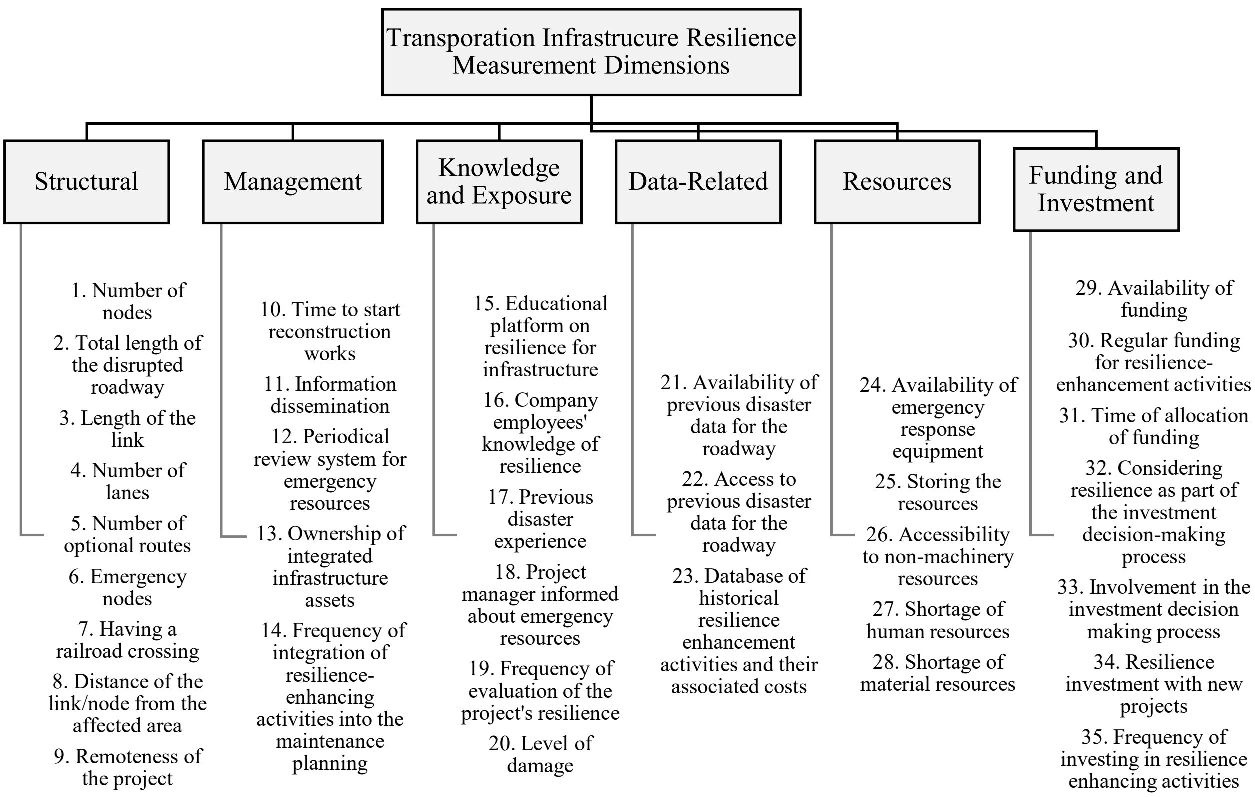
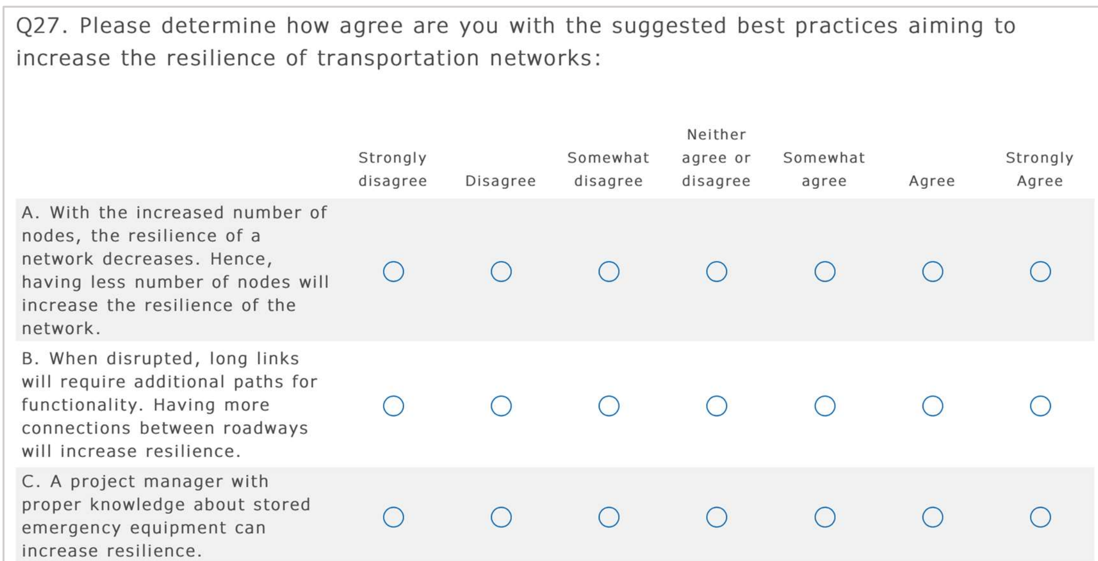


Figure 4. Variables to Quantify Resilience of Transportation Infrastructure

4.4. Survey Administration

4.1.1. Survey Development

Experts' opinions were collected via a structured survey. A survey converted dimensions into questions. The platform QuestionPro was used to develop the survey that consisted of a total of 43 questions. To make the survey simple and organized for the participants, the questions were divided into five sections: demographic-based questions, project-based questions, the concept of resilience-based questions, resilience dimensions-based questions, and best practices-related questions. A combination of Likert-scale, continuous, and open-ended questions was used for developing the survey. An introduction was provided wherein the authors explained how to correctly complete the survey, the participants were told that completing it was voluntary and that it would require about 15 minutes to complete. Samples of the survey questions are provided in Figure 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. Sample from the Survey

4.1.2. IRB Approval

After the survey was developed, it was sent to the Institutional Review Board (IRB) of the University of Texas at Arlington (UTA). IRB is the entity that crosschecks every survey/experiment conducted by the faculty, students, and staff of UTA that includes human subjects in order to make sure that their welfare is protected, and proper consent of the participants is obtained. The authors completed the required forms and submitted the documents along with the survey to IRB for approval. They also reported that the survey participants were adults and that the survey's level of risk was minimal. After making multiple modifications that were suggested by the committee members of the IRB, the survey was approved for distribution in June 2021.

4.1.3. Potential Key Participants

The research team focused primarily on experts in the field of transportation and developed a list of potential survey participants that consisted of directors and their assistants, engineers, supervisors, FEMA personnel, and others. An invitation was emailed to each potential respondent and included instructions on how to participate. All of the invitees were told that their participation was voluntary, and no compensation would be given.

4.1.4. Survey Collection

The team sent multiple email reminders to the potential survey participants resulting in 92 responses. The survey response data were downloaded from QuestionPro for further analysis.

4.5. Statistical Tests to be Performed

Since the survey had multiple types of questions (Likert-scale, continuous, and open-ended), the authors chose to perform the Kruskal-Wallis test, and two-sample t-test to identify the significant variables. Table 5 shows the assumptions and equations used to perform each particular test. Tests were performed to determine whether there was a difference between the averages of the actual observed value and the expected value.

Table 5. Statistical Tests

Test	Equation	Assumption	Reference
Kruskal-Wallis test	$H = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_i - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}\left(r_{ij} - \bar{r}\right)^2}$ 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 - $\bar{r}$ is the average of all r_{ij}	- Two groups follow an identically scaled distribution. - Each project was independent of other projects. - Used for Likert-scale type of questions	*(75)*
Two-sample t-test	$t = \frac{\bar{y}_1 - \bar{y}_2}{s}\sqrt{\frac{n_1 n_2}{n_1+n_2}}$ $s = \frac{\sum_{i=1}^{n_1}(y_{1i}-\bar{y}_1)+\sum_{i=1}^{n_2}(y_{2i}-\bar{y}_2)}{n_1+n_2-2}$ Where, - y is variables - n is the number of variables in a group - Numerical numbers are population 1 and population 2 - s is the standard deviation between two groups	- Two projects follow a normal distribution. - Each project was independent of other projects. - Used for response with count or numerical value.	*(76)*

Chi-squared test	$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i},$$ Where, N is the number of cells in the table, O is the observed value, and E is the expected value.	- Each project is independent of other project.	*(77)*
Cohen's d method	$$d = \frac{\bar{X}_1 - \bar{X}_2}{S}$$ $$S^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}$$ Where, X_1 and X_2 are two independent variables, n is the sample size, and s is the standard deviation.	- Groups are independent.	*(78)*
Rank-sum method	$$S_i = N - R_i + 1$$ $$w_i = \frac{s_T}{\sum_{j=1}^{N} s_j}$$ Where, N is the number of variables R_i is the rank of a i-th variable W_i is the weight of the i-th variable, and S_i is the score of the i-th variable.		*(79)*

5. ANALYSIS AND FINDINGS

5.1. Descriptive Data Analysis

5.1.1. Based on the Organization

Keeping the scope of the study in mind, the authors contacted personnel 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. It was found, based on the analysis performed of the responses, that the majority (53%) of the participants were affiliated with cities and counties, 27% were associated with state DOTs, and 9% had worked with the FHWA (Figure 6).

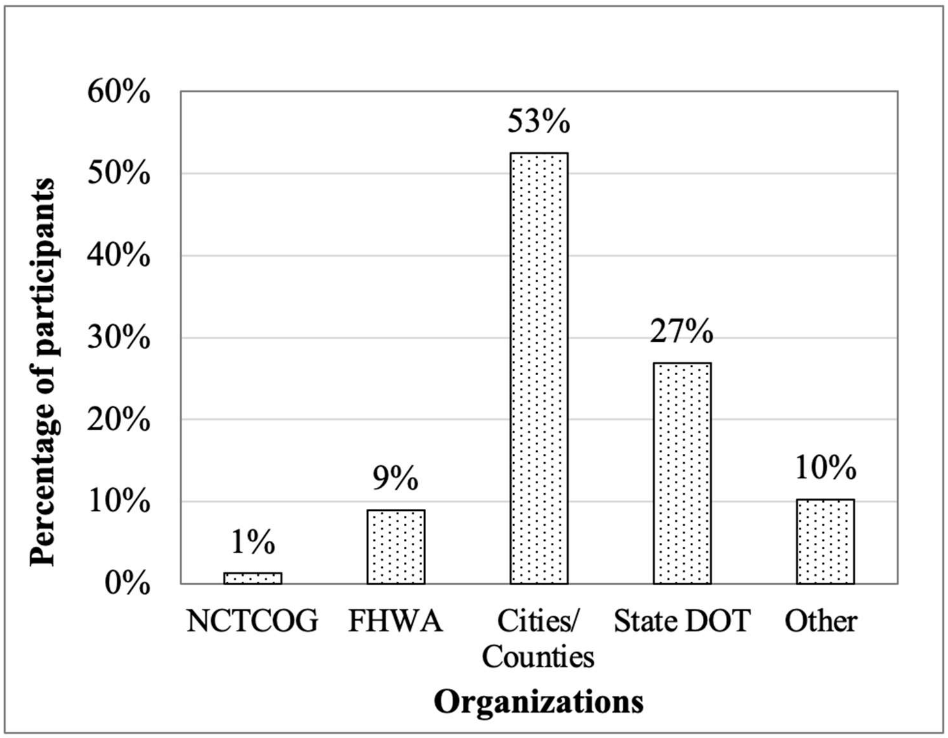


Figure 6. Distribution of the Participants based on Organization

5.1.2. Based on Year of Experience

Demographic data regarding the respondents' years of experience working at different transportation agencies were analyzed and revealed that 41% of the participants had more than 25 years of experience working in the field of transportation, and 19% had 20 to 25 years of experience working in the field of transportation. In a nutshell, the majority of the participants had worked at state, national, and international transportation agencies for more than 20 years. (See Figure 7.)

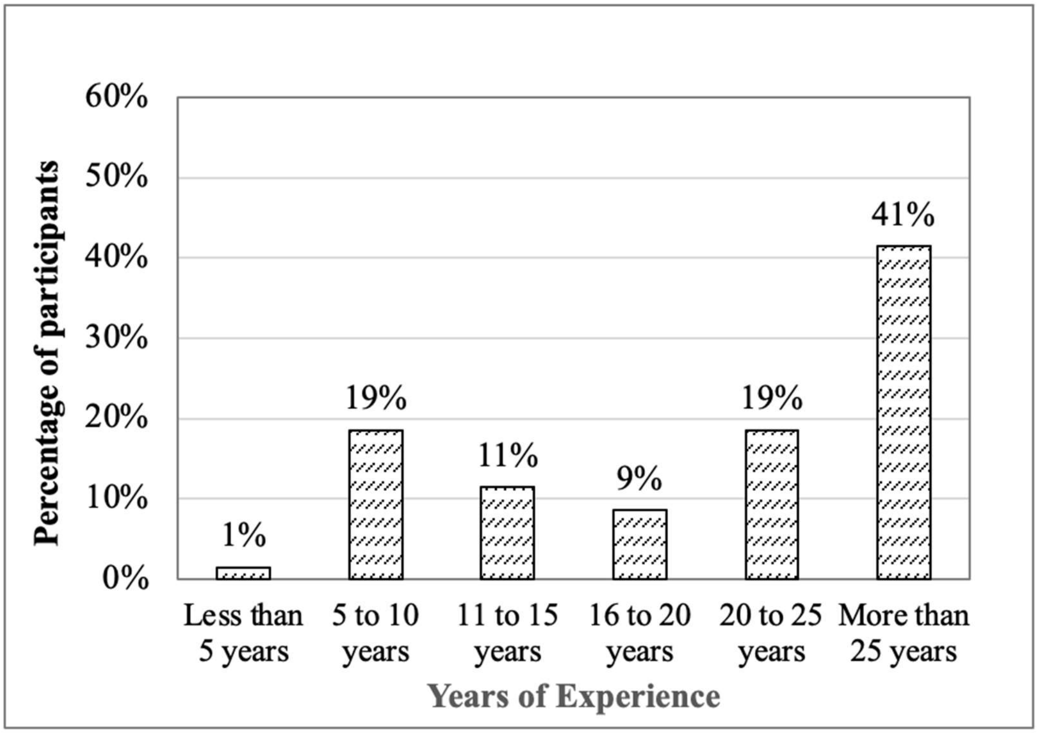


Figure 7. Distribution of the Participants based on Organization and Years of Experience

5.1.3. Based on Responsibility

The respondents to the survey were individuals with various levels of authority and a variety of job responsibilities. Figure 8 shows that 32% of the participants' job responsibilities indicated that they had a position related to directorial and supervising positions. For example, this category consisted of directors, deputy directors, and program supervisors, and 25% and 23% of the participants had performed works related to engineering and managerial positions, respectively. A few examples of these two categories are project engineers, city engineers, city managers, project managers, program managers, etc. Those from planning, administrative, safety, and inspection departments were also participants; however, the majority of the participants had more than 20 years of working experience in positions with a high level of authority.

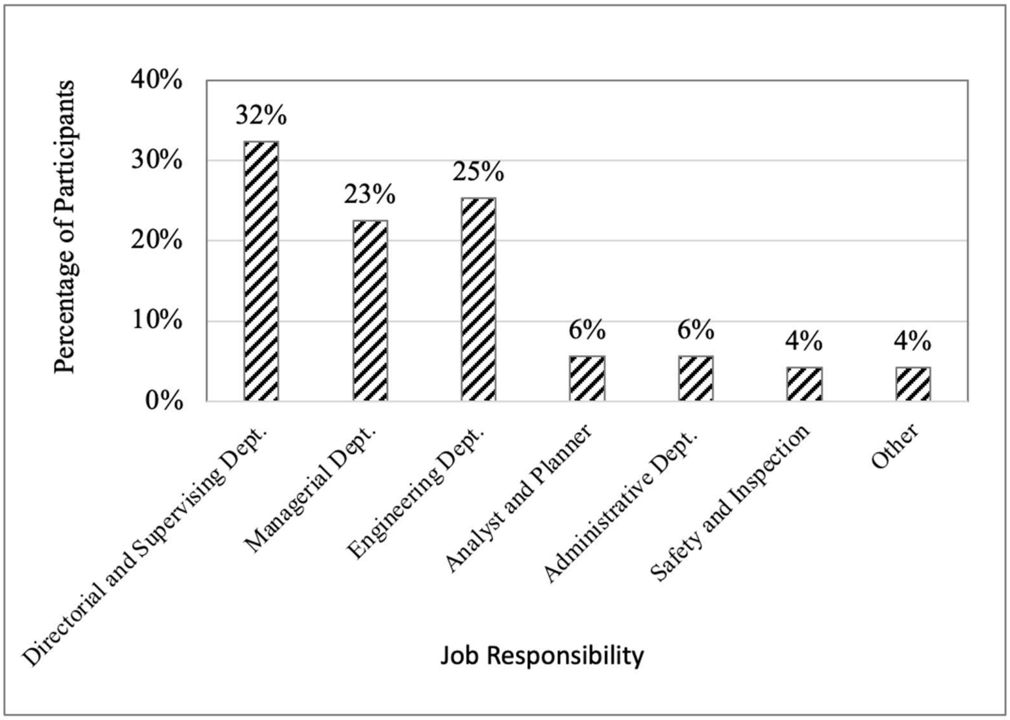


Figure 8. Distribution of the Participants based on Job Responsibility

5.1.4. Based on the Involvement in the Reconstruction of the Transportation Projects

Some of the survey questions related to the participant's involvement in reconstruction projects, and from Figure 9, it can be seen that 73% of the participants were involved in the reconstruction of transportation infrastructure at least once during their career.

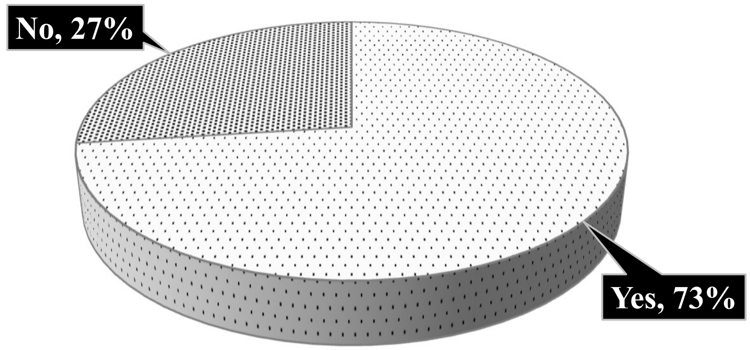


Figure 9. Involvement in the Reconstruction of Transportation Infrastructure Projects

The reconstruction of transportation infrastructures can result from any kind of disaster, but Figure 10 shows that 50% of the reconstruction work experienced by the participants was due to disastrous floods. The second-highest number of reconstruction works were performed after a hurricane (25%). Floods and hurricanes are the two most common disasters in the state of Texas, hence, the experience possessed by the participants is highly useful in the context of this study.

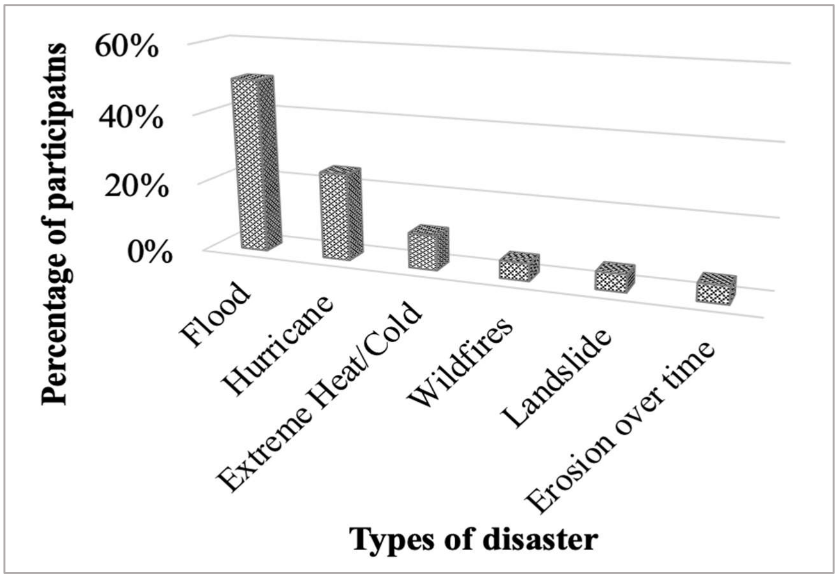


Figure 10. Distribution of the Participants based on Types of Disasters

Figure 11 shows that 66% of the reconstruction projects were roadways, 22% were highways, 10% were bridges, and the remaining 2% were ports and harbors.

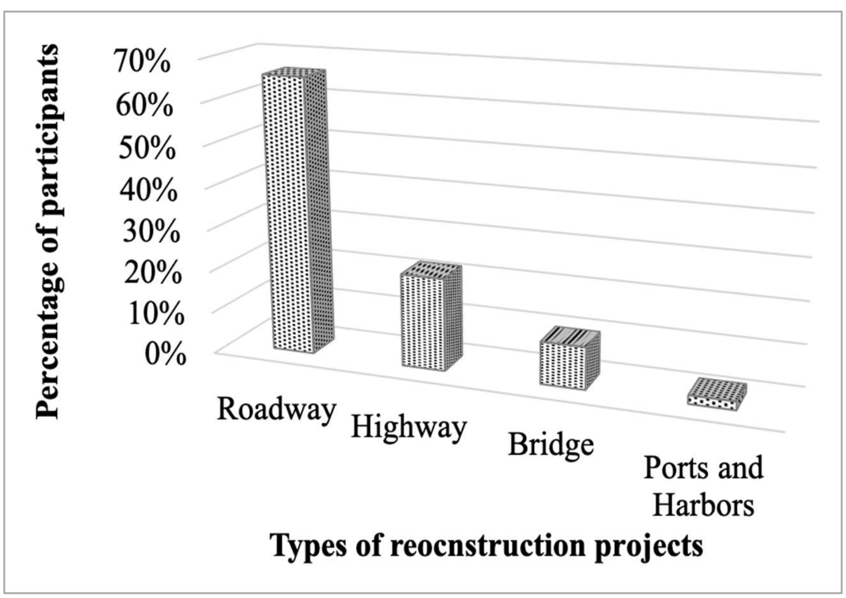


Figure 11. Distribution of the Participants based on Types of Reconstruction Projects

The participants were asked to provide the approximate value of the reconstruction projects that they were involved with, and they revealed that 26% of projects had a budget of more than $25 million (Figure 12); only 22% of the projects had a budget of less than $1 million. In summary, the participants of the survey had been involved with reconstruction projects ranging from small to large.

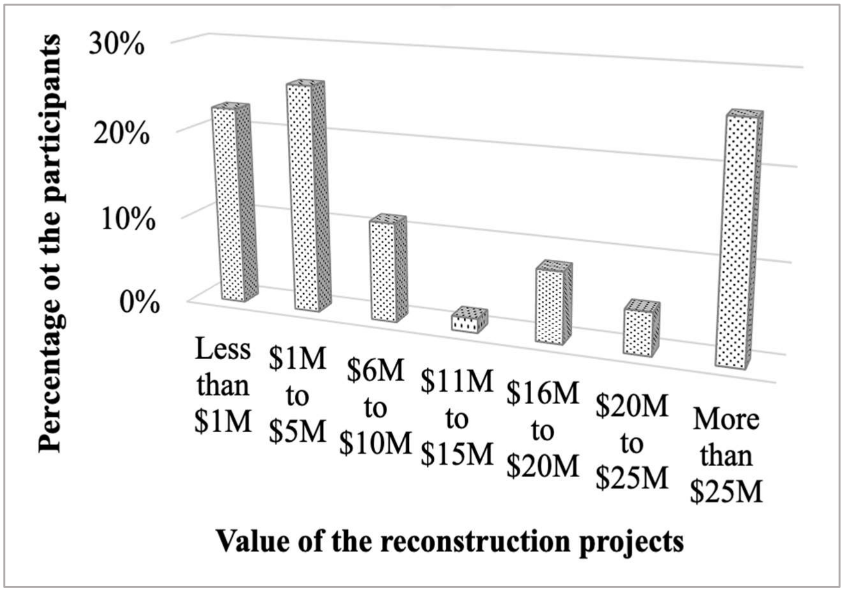


Figure 12. Distribution of the Participants based on Value of the Reconstruction Projects

The survey contained questions regarding the complexity of the reconstruction projects with which the participants had experience. The survey results were analyzed and the graphical representation (Figure 13) shows that 22% of the participants had experience working with highly complex projects, 33% with moderately complex projects, and 45% with slightly complex projects.

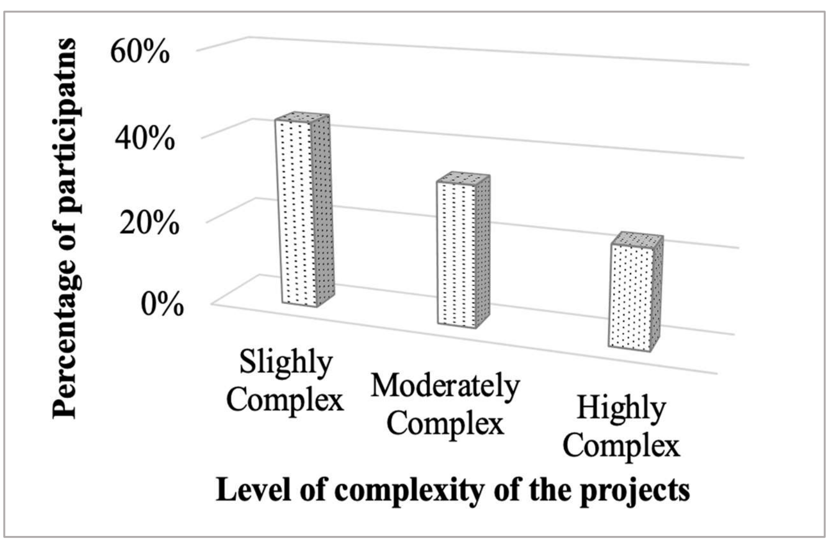


Figure 13. Distribution of the Participants based on Level of Complexity

In a nutshell, the values of the above reconstruction projects ranged from less than $1M (26%) to more than $25M (26%). This indicates that the participants had experience working on simple transportation reconstruction projects with a very limited budget as well as complex projects with a significant budget.

5.1.5. Based on Familiarity with the Concept of Resilience

The concept of resilience in transportation infrastructures has gained in popularity rapidly. However, to understand this popularity in the context of practitioners, the authors included questions regarding their familiarity with the concept. It was astonishing to find that despite 60% of the participants having more than 20 years of experience in the transportation field, only 45% of them were aware of the concept of resilience, 25% were somewhat familiar with it, and 30% were completely unfamiliar with it.

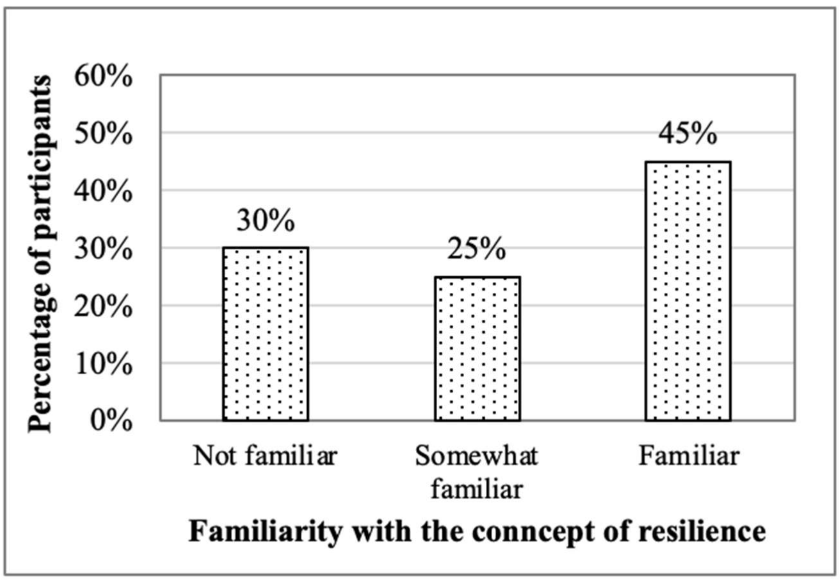


Figure 14. Distribution of the Participants based on Familiarity with the Concept of Resilience

To better understand the perspectives of the participants regarding the concept of resilience, the survey asked whether they agreed with the statement "Improving resilience is better than investing in recovery." The results in Figure 15 show that only 35% of the participants agreed with the statement; 29% disagreed and believe that investing in resilience-enhancing activities instead of recovery activities is not a cost-effective decision.

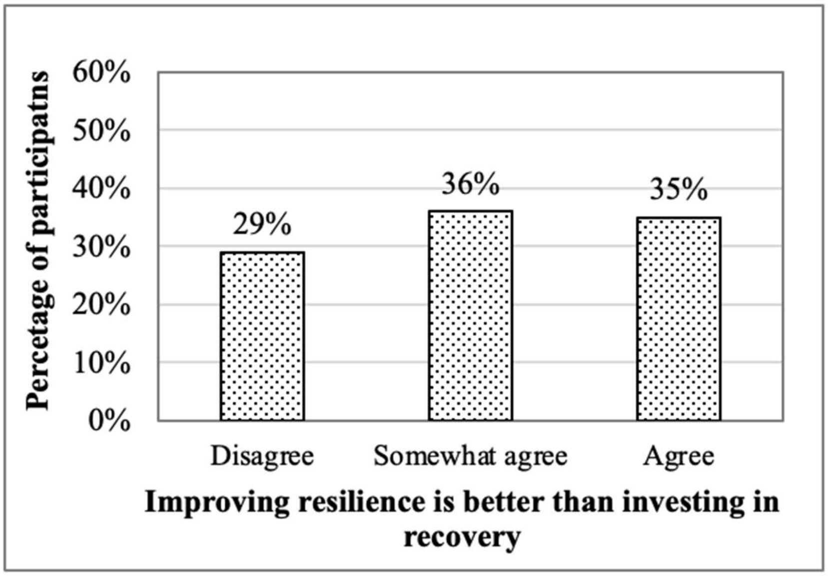


Figure 15. Distribution of the Participants Based on Agreement with the Saying "Improving resilience is better than investing in recovery."

5.2. Statistical Analysis

5.2.1. Identification of significant variables

Table 6 shows the significant variables found under the criteria involvement in the reconstruction activities. After performing the Kruskal-Wallis test and two-sample t-test, seventeen variables were found to be statistically significant.

Form the category structural, six variables were found to be significant with a p-value less than 0.1. The significant variables are the total length of the disrupted roadway, length of the link, number of lanes, number of optional routes, having a railroad crossing, and distance of the link/node from the affected area.

From the category construction management, there were two significant variables namely time to start reconstruction works, ownership of integrated infrastructure assets. People experienced with reconstruction works find that start of reconstruction work will highly influence the overall recovery time and cost of the project. Also, while working in the reconstruction projects, they found that multiple ownership creates conflicts, and managing such conflicts will slower the recovery speed after a disaster.

Table 6. List of Significant Variables Based on Project Complexity

Category	#	Variable name	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*
Construction and Management	V10	Time to start reconstruction works	0.086*
Construction and Management	V13	Ownership of integrated infrastructure assets	0.008**
Construction and 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 Experience	V16	Company employees' knowledge on resilience	0.097*
Knowledge and Experience	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 (human and materials 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 for investing on resilience enhancing activities	0.054*

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

From the knowledge and experience category, there are two significant variables namely company employees' knowledge of resilience and frequency of evaluation of resilience in the project. According to the participants experienced with previous reconstruction projects, employees' knowledge of resilience and the frequency of evaluation of resilience in the project will have an impact on the level of resilience.

From the data-related category, there are two significant variables namely availability of previous disaster data for the roadway, and access to previous disaster data for the roadway. Reconstruction projects will be difficult to perform if the previous disaster data are not available for the disaster, since such data helps in predicting the cost and effectiveness of the particular activity.

Category resources have two significant variables named availability of emergency response equipment and accessibility to non-machinery resources (human and materials resources). People with experience in the field of reconstruction view having enough emergency response equipment available as critical for faster recovery.

The funding and investment category has two significant variables namely resilience investment with new projects and frequency for investing in resilience enhancing activities. It is important to have enough monetary resources allocated for resilience enhancement activities for handling the disastrous event.

5.2.2. Development of resilience measurement tool

Weighing of Significant Variables: Different factors will make transportation infrastructure projects vulnerable at different levels. Likewise, not all variables will have the same amount of impact on the resilience of the transportation infrastructures. The team used Cohen's d method to determine the effect size of the variables. Table 7 shows the values of Cohen's d tests for the dimensions.

Table 7. Effect Size of the Dimensions over Resilience of the Transportation Infrastructures

#	Resilience measurement dimensions	Cohen's d value
2	Total length of the disrupted roadway	0.495
3	Length of the link	0.949
4	Number of lanes	0.765
5	Number of optional routes	0.895
7	Having a railroad crossing	0.767
8	Remoteness of the project	0.656
9	Distance of the link/node from the affected area	0.066
11	Time to start reconstruction works	0.96
13	Frequency of integration of resilience enhancing activities into the maintenance planning	0.313
15	Ownership of integrated infrastructure assets	0.809
16	Educational platform on resilience for infrastructure	0.318
17	Company employees' knowledge of resilience	0.702
21	Frequency of evaluation of resilience in the project	0.328
22	Availability of previous disaster data for the roadway	1.106
23	Access to previous disaster data for the roadway	0.879
27	Availability of emergency response equipment	0.807
29	Accessibility to non-machinery resources (human and material)	0.41
31	Regular funding to resilience enhancement activities	0.73
32	Time of allocation of funding	0.73
35	Resilience investment with new projects	1.255
36	Frequency of investing in resilience enhancing activities	0.676

Ranking of the Significant Variables: Cohen's d value was normalized and based on the normalized Cohen's d value variables were ranked from the highest effect size to the lowest effect size. Results are shown in Table 8. It is found that variable 34 which is resilience investment with new projects had the highest normalized effect size of 0.086. Variable 8 which is the availability of previous disaster data for the roadway had the second highest normalized effect size of 0.075. Based on the size of the effects, variables were ranked from maximum effect size to minimum effect size, maximum being rank 1 and minimum being rank 21.

Table 8. Ranking of the Variables Based on the Normalized Effect Size

#	Dimensions	Cohen's d-value	Normalized Cohen's d value	Rank
2	Total length of the disrupted roadway	0.495	0.0339	16
3	Length of the link	0.949	0.0649	4
4	Number of lanes	0.765	0.0523	10
5	Number of optional routes	0.895	0.0612	5
7	Having a railroad crossing	0.767	0.0525	9
8	Remoteness of the project	0.656	0.0449	15
9	Distance of the link/node from the affected area	0.066	0.0045	21
11	Time to start reconstruction works	0.96	0.0657	3
13	Frequency of integration of resilience enhancing activities into the maintenance planning	0.313	0.0214	20
15	Ownership of integrated infrastructure assets	0.809	0.0554	7
16	Educational platform on resilience for infrastructure	0.318	0.0218	19
17	Company employees' knowledge of resilience	0.702	0.0480	13
21	Frequency of evaluation of resilience in the project	0.328	0.0224	18
22	Availability of previous disaster data for the roadway	1.106	0.0757	2
23	Access to previous disaster data for the roadway	0.879	0.0601	6
27	Availability of emergency response equipment	0.807	0.0552	8
29	Accessibility to non-machinery resources (human and material)	0.41	0.0281	17
31	Regular funding to resilience enhancement activities	0.73	0.0499	11
32	Time of allocation of funding	0.73	0.0499	12
35	Resilience investment with new projects	1.255	0.0859	1
36	Frequency of investing in resilience enhancing activities	0.676	0.0463	14

Assigning Weights for the Variables: Ranked variables were organized incrementally and the Rank-sum method was applied. In this method ranked 1 variable was given a score of 21, the second-highest ranked variable was given a score of 20, and subsequent variables were scored similarly. The last variable was given a score of 1. Universal weight was determined using the formula mentioned in the methodology section. The results of the above-mentioned calculations are shown in Table 9. Number 1 ranked variable which is resilience investment with new projects had a maximum weight of 0.09. This value illustrates that roughly 9% of the difference in resilience level will occur if the company does not practice allocating a percentage of the budget for the resilience activities while planning for a new project. Similarly, effects of other variables can be explained based on their weights.

Table 9. Assigning Weights for the Variables

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

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 10.

Table 10. Scale for the Resilience Measurement Tool

#	Dimensions	Measures	Scale points		
1	Resilience investment with new projects	Rarely	1	2	3
		Often time	4	5	6
		Regular	7	8	9
2	Availability of previous disaster data for the roadway	Limited data	1	2	3
		Just enough data	4	5	6
		Elaborate data	7	8	9
3	Time to start reconstruction works	After a long time	1	2	3
		After a while	4	5	6
		Immediately after	7	8	9
4	Length of the link	Long length	1	2	3
		Medium length	4	5	6
		Short length	7	8	9
5	Number of optional routes	Low number	1	2	3
		Medium number	4	5	6
		High number	7	8	9
6	Access to previous disaster data for the roadway	Difficult to access	1	2	3
		Access with permission	4	5	6
		Easily accessible	7	8	9
7	Ownership of integrated infrastructure assets	Multiple ownership	1	2	3
		Limited number of ownerships	4	5	6
		Few ownership	7	8	9
8	Availability of emergency response equipment	Few available	1	2	3
		Enough available	4	5	6
		Abundantly available	7	8	9
9	Having a railroad crossing	Multiple crossings	1	2	3
		Limited crossings	4	5	6
		Few crossings	7	8	9
10	Number of lanes	Low number	1	2	3
		Medium number	4	5	6
		High number	7	8	9
11		Seldom funding	1	2	3

	Regular funding to resilience enhancement activities	Often funding	4	5	6
		Regular funding	7	8	9
12	Time of allocation of funding	Only after major disaster	1	2	3
		After almost every disaster	4	5	6
		Periodical funding irrespective of disaster	7	8	9
13	Company employees' knowledge of resilience	New to work	1	2	3
		Had little experience	4	5	6
		Expert	7	8	9
14	Frequency of investing in resilience enhancing activities	Invests rarely	1	2	3
		Invests sometimes	4	5	6
		Invests regularly	7	8	9
15	Remoteness of the project	Inside the epicenter	1	2	3
		Outside the epicenter	4	5	6
		Far from the epicenter	7	8	9
16	Total length of the disrupted roadway	Long length	1	2	3
		Medium length	4	5	6
		Short length	7	8	9
17	Accessibility to non-machinery resources (human and material)	High difficulty in access	1	2	3
		Medium difficulty in access	4	5	6
		Easy to access	7	8	9
18	Frequency of evaluation of resilience in the project	Seldom quantifies resilience	1	2	3
		Often quantifies resilience	4	5	6
		Regularly quantifies resilience	7	8	9
19	Educational platform on resilience for infrastructure	Seldom review sessions	1	2	3
		Sometimes review sessions	4	5	6
		Regular review sessions	7	8	9
20	Frequency of integration of resilience enhancing activities into the maintenance planning	Low	1	2	3
		Medium	4	5	6
		High	7	8	9
21	Distance of the link/node from the affected area	Low	1	2	3
		Medium	4	5	6
		High	7	8	9

Resilience Calculation using the Tool: This will be an excel based resilience measurement tool to quantify the resilience of the transportation infrastructures. 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 9. 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.

$$Resilience\ impact\ value\ of\ the\ variable = Weight\ of\ the\ dimension * Score\ of\ the\ dimension$$

$$Level\ of\ resilience\ of\ the\ transportation\ infrastructure = \sum_{Variable\ 1}^{Variable\ 21} Resileince\ impact\ value\ of\ the\ dimension$$

Table 11 shows the output window of the developed decision-making tool. The score which will be provided by the users from the scale (Table 10) 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 the cumulation of resilience impact values that is the last column of the table. The different projects can utilize this tool to determine the level of resilience of the project and a decision-person can make a judgment by comparing the level of resilience of the projects.

Table 11. Calculation of Resilience Using the Developed Tool

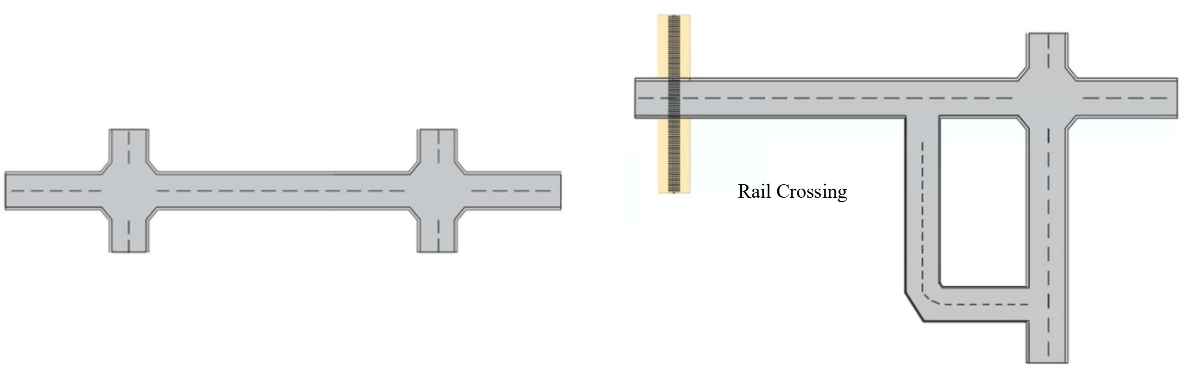
#	Resilience Dimensions	Weights	Project 1	
			Score selection from the scale	Resilience Impact Value (RIV) = Weights * Score
1	Resilience investment with projects	0.091		
2	Availability of previous disaster data for the roadway	0.087		
3	Time to start reconstruction works	0.082		
4	Length of the link	0.078		
5	Number of optional routes	0.074		
6	Access to previous disaster data for the roadway	0.069		
7	Ownership of integrated infrastructure assets	0.065		
8	Availability of emergency response equipment	0.061		
9	Having a railroad crossing	0.056		
10	Number of lanes	0.052		
11	Regular funding to resilience enhancement activities	0.048		
12	Time of allocation of funding	0.043		
13	Company employees' knowledge on resilience	0.039		

14	Frequency of investing on resilience enhancing activities	0.035		
15	Remoteness of the project	0.03		
16	Total length of the disrupted roadway	0.026		
17	Accessibility to non-machinery resources (human and material)	0.022		
18	Frequency of evaluation resilience in the project	0.017		
19	Educational platform on resilience for infrastructure	0.013		
20	Frequency of integration of resilience enhancing activities into the maintenance planning	0.009		
21	Distance of the link/node from the affected area	0.004		
Resilience level, RL (total of resilience impact values) =				

Validation of the Tool: To fulfill the purpose of this study, a decision-making tool based on the resilience dimensions is developed. To validate the developed resilience measurement tool, a case study is described in this section.

Suppose there are two projects with resilience enhancement needs and there are limited available resources to be allocated. The authorities need to make an informed decision to focus on one project at a specific point in time.

Project 1 – An organization that regularly measures and monitors the resilience level of its existing roadway infrastructure has applied for funding to enhance the resilience of its two-way two-lane roadway. This roadway has multiple energy conduits running under the infrastructure with multiple ownerships. Figure 16(a) shows the layout of this project. The organization is aware of the sudden need for emergency response equipment and possesses the necessary equipment in case of an emergency. The organization also meticulously collected all the historical disaster data indicating the date and extent of damages to that particular roadway based on the event type.



(a) Layout of Project 1 (b) Layout of Project 2

Figure 16. Layouts of the Example Projects

Project 2 – An organization that mainly focuses on constructing new projects is tasked to perform resilience enhancement activities. The roadway network consists of a link, a node, and a railroad crossing. A simple layout of Project 2 is shown in Figure 16(b). However, data pertaining to the previous disasters which had damaged that particular roadway, along with related reconstruction activities and costs, were not documented. Since the organization's focus is constructing new projects, they are not much familiar with the concept of resilience.

Based on these two projects, the responsible person will select a scale point using Table 10 for comparison purposes. Other proper assumptions are made while completing the template. Table 12 highlights the resultant score selection values for each project along with the other calculations.

Table 12. Example Usage of the Resilience Measurement Tool

#	Resilience Dimensions	Weights	Project 1		Project 2	
			Score selection	Resilience value = Weights * Score	Score selection	Resilience value = Weights * Score
1	Resilience investment with projects	0.091	7	0.637	2	0.182
2	Availability of previous disaster data for the roadway	0.087	8	0.696	1	0.087
3	Time to start reconstruction works	0.082	0	0	0	0
4	Length of the link	0.078	5	0.39	8	0.624
5	Number of optional routes	0.074	1	0.074	5	0.37
6	Access to previous disaster data for the roadway	0.069	8	0.552	1	0.069
7	Ownership of integrated infrastructure assets	0.065	2	0.13	7	0.455
8	Availability of emergency response equipment	0.061	8	0.488	5	0.305
9	Having a railroad crossing	0.056	9	0.504	7	0.392
10	Number of lanes	0.052	3	0.156	3	0.156
11	Regular funding to resilience enhancement activities	0.048	7	0.336	1	0.048
12	Time of allocation of funding	0.043	0	0	0	0
13	Company employees' knowledge on resilience	0.039	0	0	0	0

14	Frequency of investing on resilience enhancing activities	0.035	5	0.175	1	0.035
15	Remoteness of the project	0.03	0	0	0	0
16	Total length of the disrupted roadway	0.026	0	0	0	0
17	Accessibility to non-machinery resources (human and material)	0.022	7	0.154	7	0.154
18	Frequency of evaluation resilience in the project	0.017	7	0.119	1	0.017
19	Educational platform on resilience for infrastructure	0.013	8	0.104	1	0.013
20	Frequency of integration of resilience enhancing activities into the maintenance planning	0.009	0	0	0	0
21	Distance of the link/node from the affected area	0.004	0	0	0	0
Total				**4.515**		**2.907**

The total row in Table 12 indicates that the roadway segment of Project 1 is more resilient compared to the roadway segment of Project 2 since the summation of resilience values for Project 1 at 4.515 is larger than the 2.907 relative resilience level for Project 2. Hence, the decision-makers may decide to focus on enhancing the resilience of the roadway segment in Project 2 beforehand.

5.2.3. Development of causal model to identify most impactful factors in transportation infrastructure resilience model

Dimensions reduction: Exploratory Factor Analysis

The significant variables were needed to be reduced for further analysis. Exploratory factor analyses were performed to reduce the factors into different groups. The process of EFA was conducted using the software SPSS. The process of EFA is explained in the following sections.

Data Suitability Check: Data were checked for suitability to perform EFA. 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. The KMO value for this dataset was found to be 0.624 which is greater than the cut-off point of 0.5 (Table 13). 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 indicates that the variables are correlated in some way to perform EFA.

Table 13. Data Suitability Check for Exploratory Factor Analysis

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.624
Bartlett's Test of Sphericity	Approx. Chi-Square	277.127
	df	55
	Sig.	<.001

Authors recorded the determinant of the correlation matrix and found the determinant value as 0.041which is greater than 0.0001 (Table 14). This indicates that there is no multicollinearity in the data and the data is good to perform factor analysis.

Table 14. Determinant Value for the Factors

Factors	Determinant	Recommended value
F1 and F2	0.041	>0.0001

Component Extraction Criteria: 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 15. The first component contributes to the maximum (30.562%) of the variances compared to other three components.

Table 15. Total Variance Explained

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	3.362	30.562	30.562
2	1.554	14.126	44.688
3	1.256	11.418	56.106
4	1.046	9.509	65.615

Extracted Components: Table 16 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 more than 0.5. They were divided into four groups constituting four components. The first factor had V8, V4, V7 and V13. The second components had variables V26 and V34. The third component has V16 and V21. The last component V24, V22, and V5.

Table 16. Factor Loadings

#	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 on 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		

Factor 1: Integrated Assets: The most contributing variables of this components are distance of the link/node from the affected area, number of lanes, having a railroad crossing, and ownership of the integrated infrastructure assets. Collectively they are named as integrated assets. Roadway segment/networks generally possess some integrated assets like utility conduit, rail crossings, etc. especially the city roadway segment. When such roadway segments get affected by disasters, the recovery of the roadway also depends on the recovery of any integrated assets.

Factor 2: Resources and Investment: Two variables were included in this component namely accessibility to non-machinery resources and resilience investment with new projects. Collectively they are named as resources and investment. Investment with the new projects can be segmented based on necessity. For example, a percentage of investment can be directed to ensure accessibility to non-machinery resources. Having non-machinery resources like human and material during or after the disaster for response and recovery activities will help the system to regain functionality faster and better after a disaster. Such linked behavior made these two variables to be grouped together to form Factor 2.

Factor 3: Knowledge: Factor 3 holds two variables namely company employees' knowledge on resilience and availability of previous disaster data for the roadway. A well-educated employee has the potential to make a big difference when it comes to handling aftereffect of disaster. Having a comprehensive database will highly help an employee in educating himself regarding the history, resilience activities and maintenance performed on the roadway over the years. Such positive connection between these two variables helped identify these two variables in one component.

Factor 4: Response and Resources: The variables under this component are availability of emergency response equipment, access to previous disaster data for the roadway, and number of optional routes. Variables of this component makes it easier to perform immediate response activities after a disaster. For example, having a previous disaster data will not be helpful if it is not easily accessible when needed. During emergency period, responsible person will need easy and fast access to disaster data for comparing the situation and to justify whether similar handling measure will be helpful. In this scenario, making the information online and giving access to the responsible personnel beforehand will solve the problem of accessibility of the disaster data. Similarly emergency response equipment can pave the way of faster recovery activities. Such similar and dependent behavior grouped these three variables into one factor.

Model development

As the number and type of the data which could be collected in this project was not initially known, multiple modeling techniques were considered including multinomial logistic regression, stepwise regression, artificial neural network, support vector machines (SVM), and Structural Equation Modeling (SEM). In this study, the team collected different types of data for each infrastructure case study/project and data included mix of continuous, nominal, binary, and ordinal. Table 17 presents the variables and type of data collected.

Table 17. List of Variables and Collected Data Types.

#	Variable	Type of Data
1	Number of nodes	Continuous
2	Total length of the disrupted roadway	Continuous
3	Length of the link	Continuous
4	Number of lanes	Continuous
5	Number of optional routes	Continuous
6	Emergency nodes	Ordinal
7	Having a railroad crossing	Ordinal
8	Distance of the link/node from the affected area	Ordinal
9	Remoteness of the project	Ordinal
10	Time to start reconstruction works	Continuous
11	Information dissemination	Ordinal
12	Periodical review system for emergency resources	Ordinal
13	Ownership of integrated infrastructure assets	Binary
14	Frequency of integration of resilience-enhancing activities into the maintenance planning	Continuous
15	Educational platform on resilience for infrastructure	Ordinal
16	Company employees' knowledge of resilience	Ordinal
17	Previous disaster experience	Ordinal
18	Project manager informed about emergency resources	Ordinal
19	Frequency of evaluation of the project's resilience	Continuous

20	Level of damage	Continuous
21	Availability of previous disaster data for the roadway	Ordinal
22	Access to previous disaster data for the roadway	Ordinal
23	Database of historical resilience enhancement activities and their associated costs	Binary
24	Availability of emergency response equipment	Ordinal
25	Storing the resources	Binary
26	Accessibility to non-machinery resources	Binary
27	Shortage of human resources	Ordinal
28	Shortage of material resources	Ordinal
29	Availability of funding	Binary
30	Regular funding for resilience-enhancement activities	Nominal
31	Time of allocation of funding	Nominal
32	Considering resilience as part of the investment decision-making process	Binary
33	Involvement in the investment decision making process	Binary
34	Resilience investment with new projects	Continuous
35	Frequency of investing in resilience enhancing activities	Continuous

Multinomial logistic regression is used when a categorical dependent variable has two or more discrete outcomes *(80, 81)*. As the collected data included various data types, multinomial logistic regression was not the best fit for the analysis. In addition, multinomial regression modeling does not enable practitioners to rank the resilience level of their infrastructures and only categorizes the projects into multiple categories. In other words, it does not generate values to compare the resilience of two projects if they fall into the same category. Various researchers have used the stepwise regression model as an appropriate analysis only if there is a need to identify a useful subset of the predictors *(82, 83)*. Since there were several different types of variables which were significant to measurement of resilience in this project, stepwise regression would have not resulted in yielding the most accurate result. Therefore, the team has utilized Factor Analysis to reduce the dimensions of the model. As another modeling technique, artificial neural network modeling was initially considered. However, this model was not considered the best fit as it is difficult to evaluate the influence of cluster of independent variables on dependent variable *(84, 85)*. Regarding adoption of SVM, several scholars have only used this technique in their analysis when there is an understandable margin of dissociation between classes *(86, 87), wh*ich was not applicable to the collected data.

Therefore, based on the type of collected data, the SEM modeling technique was chosen as the best fit, and a model was developed using SPSS AMOS to build and analyze the potential relationship among and between the components, and resilience measurement dimensions. SEM analysis not only validates hypothesized relationships but also explores new relationships. Moreover, SEM is efficient in handling complex dependencies and provides flexibility with sample numbers *(88, 89)*. In addition, Cohen's d method, rank-sum method, and factor analysis method were also utilized. Cohen's d method was utilized to determine the effect size of the variables, the rank-sum method was used to assign weight to the variables, and factor analysis technique was used to identify latent variables which cannot be measured through direct data collection. The schematic process which led to the model development is presented in Figure 17. The following sections explain the model in detail.

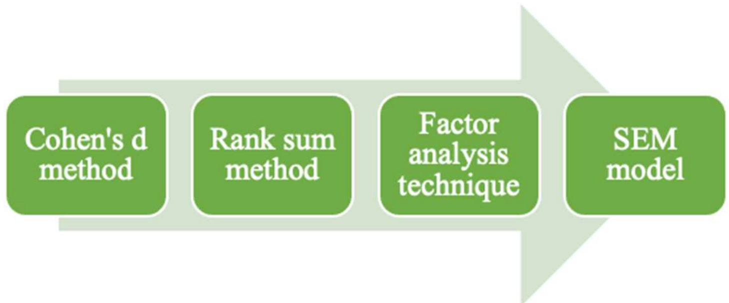


Figure 17. Schematic Process that Led to Model Development

Hypotheses for the model: Based on the components developed above and literature review four hypothesis were developed to address in the model.

H1. Integrated assets of the roadway have an impact on rapidity.
H2. Resources and investment of the project has impact on rapidity.
H3. Knowledge has impact on rapidity.
H4. Emergency resources have impact on rapidity.

Model analysis

The hypothesized relationships were introduced in the SPSS AMOS for analysis. Resilience measure rapidity was also introduced in the software. Together they built the model by showing relationships with one-sided arrow, co-relationship with two-sided arrow, observable variables with rectangles and latent variables with eclipse. The model was run and check for goodness of fit.

A good fitted structural equation model must fit into four fit indexes namely χ^2/df, RMSEA, CFI, and PNFI *(89)*. Table 18 shows the fit indexes value along with the corresponding recommended values. For the developed model, χ^2/df was found to be 1.722 (<3), RMSEA found to be 0.089 (<0.1), CFI found to be 0.91 (>0.9) and PNFI found to be 0.51 (>0.5). Such values indicate good fit for the data to explore the relationships and co-relationships.

Table 18. Comparison of Fit Indexes

Fit Indexes	Values	Recommended values *(89)*	Fit
Chi-square (χ^2)	60.258	-	-
Degree of freedom (df)	35	-	-
χ^2/df	1.722	<3.00	Good fit
Absolute fit RMSEA (root mean square residual)	0.089	<0.10	Good fit
Incremental fit CFI (comparative fit index)	0.91	>0.90	Good fit
Parsimonious fit PNFI	0.51	>0.50	Good fit

Another way to check fitness of the model is through standardized residual covariances (Table 19). An absolute value of less than 3 indicates acceptable model fitness. For our model, the maximum absolute standardized residual covariance is 2.042 which is less than recommended cut off point 3.

Table 19. Residual Covariances for the SEM Model Developed for Simple and Complex Projects

	V16	**V21**	**V26**	**V34**	**Rapidity**	**V5**	**V22**	**V24**	**V4**	**V7**	**V8**
V16	.000										
V21	.000	.000									
V26	-.704	1.140	.000								
V34	-.169	.059	.000	.000							
Rapidity	-.126	.146	.229	-.097	.000						
V5	-.736	-.094	-.505	.192	.139	.000					
V22	1.207	.724	-.761	.566	-.850	-.359	.000				
V24	-.005	-.149	-.560	.069	.483	.283	.039	.000			
V4	.496	-1.009	.190	-.450	.468	1.364	-.581	.657	.000		
V7	-.347	.939	-.411	.659	-.179	-.887	.833	-1.343	-.067	.000	
V8	-.393	.037	-.262	-.331	-.628	.587	1.021	-2.042	-.238	.380	.000

The model was run for path coefficient and the values are recorded in Table 20. Table shows the relationships, the estimate and the level of significance of the paths. It was found that only except one path, 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 other parameter, a non-significant parameter should be kept in the model *(90)*.

Table 20. Path Coefficients of the SEM Model Developed Based on Complexity of the Projects

Relationships			**Estimate**	**P**
V8	<---	Integrated_Assets	.523	***
V7	<---	Integrated_Assets	.774	***
V4	<---	Integrated_Assets	.748	***
V24	<---	Emergency_Resources	.607	***
V22	<---	Emergency_Resources	.561	***
V5	<---	Emerergency_Resources	.742	***
Rapidity	<---	Integrated_Assets	-.736	***
Rapidity	<---	Emergency_Ressources	.413	***
V34	<---	Resource_Investment	.506	***
V26	<---	Ressource_Investment	.269	.118
Rapidity	<---	Ressource_Investment	.606	.704
V21	<---	Knowledge	.533	***
V16	<---	Knowledge	.577	***
Rapidity	<---	Knowledge	.239	.787

The final hypothesis model is shown in Figure 18. Latent variables integrated assets, resources and investment, and emergency resources has significant impact on the resilience measure rapidity. However, latent variable knowledge has negligible and non-significant relationship with the resilience measure rapidity when it comes to involvement in the reconstruction projects. However, knowledge has a good correlation with construct integrated assets and emergency resources.

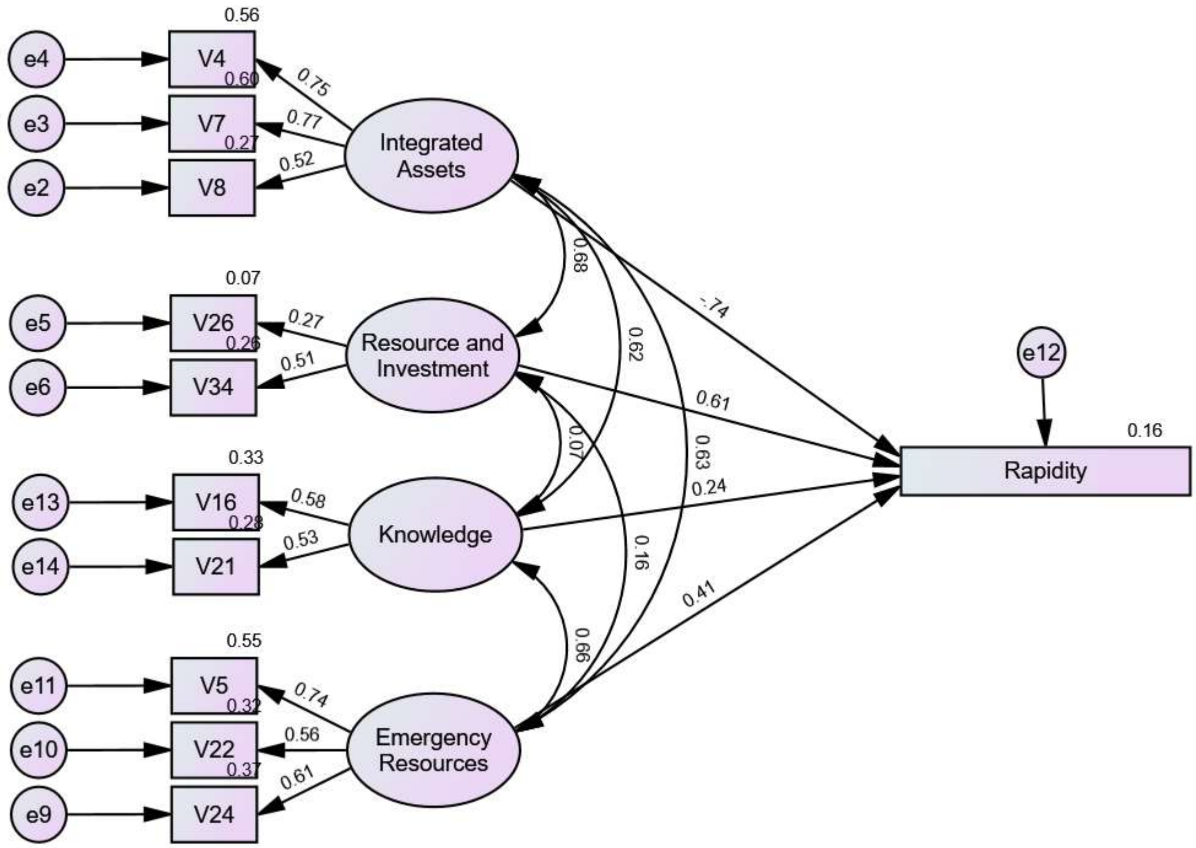


Figure 18. Testing Result of the SEM Model Showing the Impact of Variables on Rapidity Characteristics of Transportation Infrastructure Resilience under the Criteria Involvement

Discussion on Model

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

Developed model confirmed the first hypothesis that the integrated asset of a roadway has impact over rapidity. In other words, presence of integrated assets in a roadway will determine the level of resilience of the network. Authors considered number of lanes as an asset of the roadway since increased number of lanes increase the capacity of the roadway. Number of lane also helps to regain functionality after a disaster by providing the opportunity to make a lane reversible to continue traffic movement from both direction if needed after a disaster. Our model also identifies 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. Similarly, other two observable variable under this latent variable highly impact the reconstruction time and consequently impact the level of resilience of the transportation network.

H2. Resources and investment of the project has impact on rapidity.
The predictive hypothesis of resources and investment having impact over rapidity of the damaged transportation network was not supported by our model. The 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 kept in the model.

H3. Knowledge has impact on rapidity.

The adopted hypothesis that the knowledge has an impact on the rapidity of the damaged network was not supported by our model. The latent construct knowledge had a insignificant relation with the observable variable rapidity with a path coefficient of 0.24. However, the construct knowledge has 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 construct and influence 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 propagation of damage. Similarly, accessibility to disaster data for the roadway will help during immediate response phase as well as 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.

5.2.4. Identifying Most Critical Factors and Developing Corresponding Strategies

Most Critical Factors: Two radar plots are drawn to show the relative positions of variables based on their impacts compared to others (Figure 19). The combined impact of the variables is also recorded. Considering these two conditions, top 6 most critical factors in impacting resilience were listed and ranked from 1 through 6. 1 being the most impactful and 6 being the least impactful.

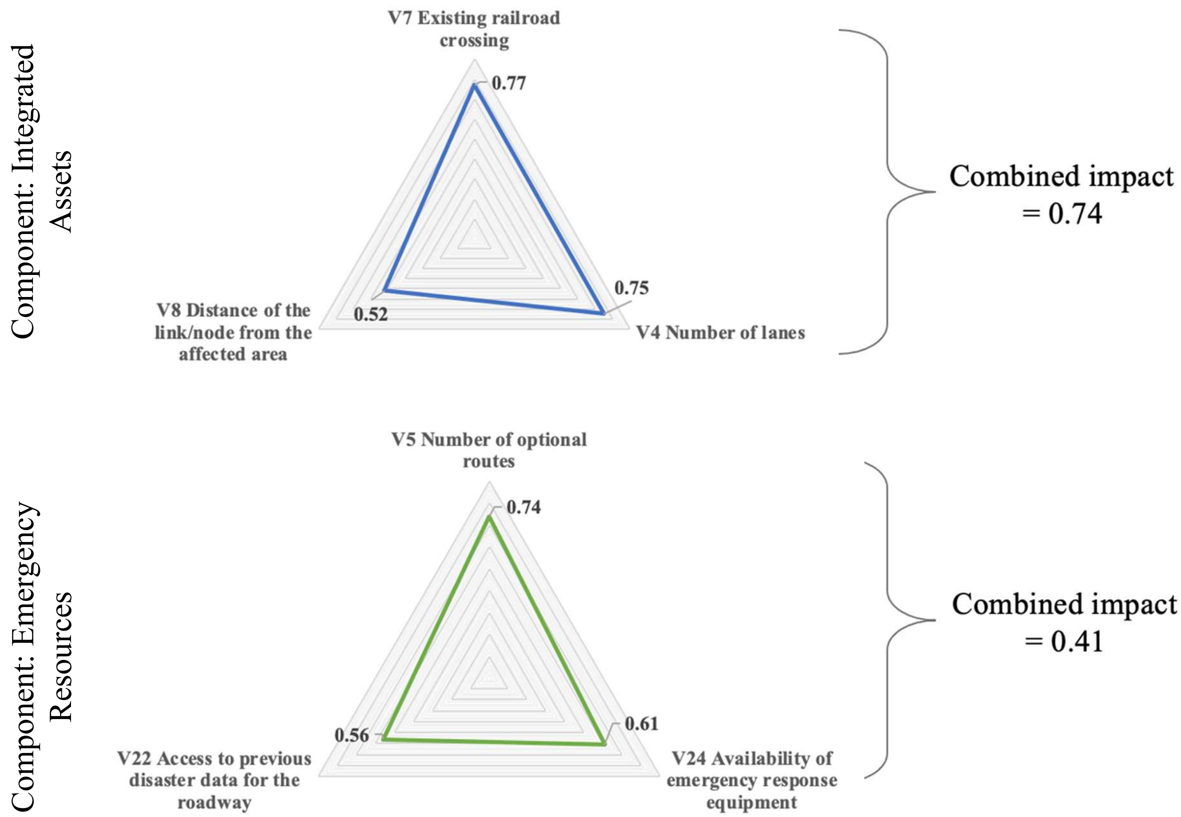


Figure 19. Radar Plots to Show Relative Impact of the Variables

Most Effective Strategies: Strategies corresponding to ranked critical factors are provided in Table 21. To avoid issues related to the first factor, one must try investing in locating integrated assets away from the roadways, so if a break in a railroad crossing or utility line occurs or emergency repairs are needed, the impact on the roadway operations can be minimized. To avoid issues related to access to previous disaster data for the roadway this study suggests investing in preparing an interactive online platform for recording and reviewing data related to disasters as well as previous resilience enhancing activities for the roadway with easy access credentials.

Table 21. Most Effective Strategies Corresponding to most Critical Factors

Rank	Factor	Strategies
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.

6	Distance of the link/node from the affected area	- Estimate probable disaster epicenters based on historical data when performing periodical disaster drill.
3	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.
4	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.
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. CONCLUSIONS

The aims of this study were to identify the factors that affect the resilience of transportation infrastructures and to develop models that can measure the level of resilience. To fulfill these goals, a questionnaire was developed which was supported by a comprehensive literature review. The survey was distributed among recipients with experience working on different transportation projects under different transportation agencies. After multiple reminder emails, 92 valid responses were collected and analyzed qualitatively and quantitatively. At this point, 35 variables of resilience measurement were listed, and statistical tests were performed to determine which were most significant. A resilience measurement tool was developed to quantify the level of resilience of different transportation infrastructure projects. Also, to develop the most effective strategies in increasing the recovery time and enhancing the resilience of the transportation infrastructures, a causal model was developed using the structural equation modeling technique. To avoid the problem of using too many variables, exploratory factor analysis was performed, and components were identified. Based on the concept of structural equation modeling (SEM), a nested model was drawn, using SPSS AMOS. Other variables were incorporated into the nested model, and after multiple trials and errors, a structural model was developed that showed all the hypothetical relationships under each criterion.

Based on the analysis, the following conclusions were drawn.

1. Even though 73% of the participants had experience working on reconstruction projects and 60% of the participants had experience working for transportation agencies for more than 20 years, only 45% of the participants were aware of the concept of resilience.
2. Twenty-one significant variables were identified to use to develop a resilience measurement model. This model will provide relative resilience to multiple transportation infrastructure projects. Based on the outcome of the tool, a person will be able to identify the less resilient network with the most vulnerability. Such identification will help in investing in resilience enhancement activities for the most vulnerable segment of the network.
3. A causal relationship model was developed using structural equation modeling to identify the most critical factors that affect the reconstruction time of transportation infrastructure reconstruction projects. This model shows the impact of four constructs namely integrated assets, resource and investment, knowledge, and emergency resource over the rapidity of the transportation infrastructure reconstruction. Collectively all the variables of the constructed integrated assets influence the rapidity of the reconstruction, however, the existence of a railroad crossing will have maximum impact. This is because a damaged railroad crossing has the potential to retard the restoration activity of the transportation network by delaying the restoration of other integrated infrastructures. Construct emergency resources has a significant direct impact on the rapidity of the transportation infrastructure reconstruction projects. This indicates that resources like emergency response equipment will lower the reconstruction time significantly. Collectively the variables under this construct will have a significant impact on rapidity but variable 5 which is the number of optional routes will have maximum impact on rapidity. This is because having available optional routes will make rerouting the traffic from the damaged area convenient and faster rerouting will ensure faster recovery of the damaged roadway.
4. This study also developed corresponding strategies to handle the critical factors that most contribute to prolonging the reconstruction time of the affected transportation infrastructures.

To avoid issues related to the first factor, one must try investing in locating integrated assets away from the roadways, so if a break in a railroad crossing or utility line occurs or emergency repairs are needed, the impact on the roadway operations can be minimized. To avoid issues related to access to previous disaster data for the roadway this study suggests investing in preparing an interactive online platform for recording and reviewing data related to disasters as well as previous resilience enhancing activities for the roadway with easy access credentials.

Despite all the benefits of this study, a limitation should be mentioned. Due to covid, the survey was conducted only via electronic media. Such constriction resulted in a limited number of valid responses, from which only three constructs could be developed, using exploratory factor analysis.

REFERENCES

1. Liao, T. Y., Hu, T. Y., & Ko, Y. N. (2018). A resilience optimization model for transportation networks under disasters. *Natural hazards*, *93*(1), 469-489.

2. Kermanshachi, S., Bergstrand, K., & Rouhanizadeh, B. (2019). Identifying, weighting and causality modeling of social and economic barriers to rapid infrastructure recovery from natural disasters: A study of hurricanes Harvey, Irma and Maria.

3. Wan, C., Yang, Z., Zhang, D., Yan, X., & Fan, S. (2018). Resilience in transportation systems: a systematic review and future directions. *Transport reviews*, *38*(4), 479-498.

4. Pamidimukkala, A., Kermanshachi, S., & Safapour, E. (2020). Challenges in Post-Disaster Housing Reconstruction: Analysis of Urban vs. Rural Communities. In *Creative Construction e-Conference 2020* (pp. 103-110). Budapest University of Technology and Economics.

5. Safapour, E., Kermanshachi, S., & Jafari, A. (2021). Investigating Implementation level of Phase-Based Strategies in Transportation Infrastructure Projects. *Canadian Journal of Civil Engineering.*

6. Mojtahedi, M., Newton, S., & Von Meding, J. (2017). Predicting the resilience of transport infrastructure to a natural disaster using Cox's proportional hazards regression model. *Natural Hazards*, *85*(2), 1119-1133.

7. Frangopol, D. M., & Bocchini, P. (2011). Resilience as optimization criterion for the rehabilitation of bridges belonging to a transportation network subject to earthquake. In *Structures Congress 2011* (pp. 2044-2055).

8. Safapour, E., Kermanshachi, S., & Pamidimukkala, A. (2021). Post-Disaster Recovery in Urban and Rural Communities: Challenges and Strategies. *International Journal of Disaster Risk Reduction,* 64(3), 102535.

9. Kermanshachi, S., Dao, B., Rouhanizadeh, B., Shane, J., & Anderson, S. (2020). Development of the project complexity assessment and management framework for heavy industrial projects. *International Journal of Construction Education and Research*, *16*(1), 24-42.

10. Rouhanizadeh, B., & Kermanshachi, S. (2020). Comparative Analysis of Public's and Decision-Makers' Perspectives on Socioeconomic Barriers Causing Delay in Post-Disaster Recovery Processes. In *Construction Research Congress 2020: Infrastructure Systems and Sustainability* (pp. 856-864). Reston, VA: American Society of Civil Engineers.

11. Heaslip, K., Louisell, W., & Collura, J. (2009). *A methodology to evaluate transportation resiliency for regional networks* (No. 09-3194).

12. Nipa, T. J., & Kermanshachi, S. (2020). Identification of the Resilience Dimensions and Determination of Their Relationships in Critical Transportation Infrastructure. In *Construction*

Research Congress 2020: Infrastructure Systems and Sustainability (pp. 644-653). Reston, VA: American Society of Civil Engineers.

13. Franchin, P., & Cavalieri, F. (2015). Probabilistic assessment of civil infrastructure resilience to earthquakes. *Computer-Aided Civil and Infrastructure Engineering*, *30*(7), 583-600.

14. Moteff, J. D. (2012). Critical infrastructure resilience: the evolution of policy and programs and issues for congress.

15. Reggiani, A. (2013). Network resilience for transport security: Some methodological considerations. *Transport Policy*, *28*, 63-68.

16. Labaka, L., Hernantes, J., & Sarriegi, J. M. (2016). A holistic framework for building critical infrastructure resilience. *Technological Forecasting and Social Change*, *103*, 21-33.

17. Nipa, T. J., Kermanshachi, S., & Ramaji, I. (2019). Comparative analysis of strengths and limitations of infrastructure resilience measurement methods. In *7th CSCE International Construction Specialty Conference (ICSC)* (pp. 12-15).

18. Rouhanizadeh, B., & Kermanshachi, S. (2019). Investigating the Relationships of Socioeconomic Factors Delaying Post-Disaster Reconstruction. In *Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience* (pp. 33-40). Reston, VA: American Society of Civil Engineers.

19. Vugrin, E. D., Warren, D. E., & Ehlen, M. A. (2011). A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress*, *30*(3), 280-290.

20. Faturechi, R., & Miller-Hooks, E. (2014). Travel time resilience of roadway networks under disaster. *Transportation research part B: methodological*, *70*, 47-64.

21. Freckleton, D., Heaslip, K., Louisell, W., & Collura, J. (2012). Evaluation of resiliency of transportation networks after disasters. *Transportation research record*, *2284*(1), 109-116.

22. Rouhanizadeh, B., & Kermanshachi, S. (2019). A Systematic Approach to Analysis and Prioritization of the Socioeconomic Policies and Legal barriers to Rapid Post Disaster Reconstruction. In *7th CSCE International Construction Specialty Conference (ICSC)* (pp. 12-15).

23. Rouhanizadeh, B., Kermanshachi, S., & Dhamangaonkar, V. S. (2020). Reconstruction of Critical and Interdependent Infrastructure Due to Catastrophic Natural Disasters: Lessons Learned. In *Construction Research Congress 2020: Infrastructure Systems and Sustainability* (pp. 895-904). Reston, VA: American Society of Civil Engineers.

24. Rouhanizadeh, B., & Kermanshachi, S. (2021). Development of a Model Determining the Relationships of the Factors Delaying Reconstruction Projects. In *International Conference on Transportation and Development 2021* (pp. 330-340).

25. Pamidimukkala, A., Kermanshachi, S., & Karthick, S. (2020). Impact of natural disasters on construction projects: Strategies to prevent cost and schedule overruns in reconstruction projects. In *Creative Construction e-Conference 2020* (pp. 49-57). Budapest University of Technology and Economics.

26. Croope, S. V., & McNeil, S. (2011). Improving resilience of critical infrastructure systems postdisaster: recovery and mitigation. *Transportation research record*, *2234*(1), 3-13.

27. Safapour, E., Kermanshachi, S., & Nipa, T. J. (2020). A Damage-based Analysis of Rework in Reconstruction of Infrastructure Projects Due to Natural Disasters. In *Creative Construction e-Conference 2020* (pp. 55-62). Budapest University of Technology and Economics.

28. Kermanshachi, S., Bergstrand, K., Zhang, Y. L., Suh, J., & Safapour, E. (2020). *Rebounding From Disruptive Events: Optimization of Post-Disaster Reconstruction Activities for Critical and Interdependent Infrastructure Networks* (No. CTEDD 019-17). Center for Transportation, Equity, Decisions and Dollars (CTEDD).

29. Safapour, E., & Kermanshachi, S. (2020). Identification and categorization of factors affecting duration of post-disaster reconstruction of interdependent transportation systems. In *Construction Research Congress 2020: Computer Applications* (pp. 1290-1299). Reston, VA: American Society of Civil Engineers.

30. Nipa, T. J., Kermanshachi, S., & Karthik, S. (2022). Analysis of Investment Decision-Making Factors in Resilience Improvement of Transportation Infrastructures. Proceedings of *Construction Research Congress (CRC).*

31. Rouhanizadeh, B., & Kermanshachi, S. (2020). Post-disaster reconstruction of transportation infrastructures: Lessons learned. *Sustainable Cities and Society*, *63*, 102505.

32. Safapour, E., Kermanshachi, S., & Nipa, T. J. (2020). Schedule Performance Analysis of Infrastructure Reconstruction Projects Due to Extreme Events. In *Creative Construction e-Conference 2020* (pp. 39-48). Budapest University of Technology and Economics.

33. Safapour, E., & Kermanshachi, S. (2021). Delay in Post-Disaster Reconstruction Projects: Analysis of Highly Damaged VS Minimally Damaged Infrastructures. ASCE International Conference on Transportation and Development.

34. Rouhanizadeh, B., & Kermanshachi, S. (2021). Barriers to an Effective Post-Recovery Process: A Comparative Analysis of the Public's and Experts' Perspectives. *International Journal of Disaster Risk Reduction* 57:102181

35. Rouhanizadeh, B., & Kermanshachi, S. (2022). Investigation of Causal Relationships among Factors Affecting Post-Disaster Reconstruction Process: Adoption of Social Network Analysis (SNA) Method. Proceedings of *Construction Research Congress (CRC).*

36. Safapour, E., & Kermanshachi, S. (2021). Reconstruction of Transportation Infrastructure with High Complexity: Mitigating Strategies for Effective Post-Disaster Reconstruction. In *International Conference on Transportation and Development 2021* (pp. 191-200).

37. Rouhanizadeh, B., Kermanshachi, S., & Safapour, E. (2021). An investigation of causal relationships among barriers that delay post-hurricane recovery of human communities. *International Journal of Disaster Risk Reduction*, 102666.

38. Adepu, N., Kermanshachi, S., Safapour, E., & Pamidimukkala, A. (2022). Challenges and Risks in Resilience Management of Water and Wastewater Infrastructures. In *Proceedings of the ASCE Construction Research Congress (CRC), Arlington, VA, USA*(pp. 9-12).

39. Kermanshachi, S., & Rouhanizadeh, B. (2018). Feasibility analysis of post disaster reconstruction alternatives using automated BIM-based construction cost estimation tool. In *Proceeding of CSCE 6th International Disaster Mitigation Specialty Conference, Montreal: Canadian Society of Civil Engineering* (pp. 13-16).

40. Safapour, E., & Kermanshachi, S. (2021). Delay in Post-Disaster Reconstruction Projects: Analysis of Highly Damaged VS Minimally Damaged Infrastructures. International Conference on Transportation and Development 2021.

41. Rouhanizadeh, B., Kermanshachi, S., & Nipa, T. J. (2019). Identification, categorization, and weighting of barriers to timely post-disaster recovery process. In *Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience* (pp. 41-49). Reston, VA: American Society of Civil Engineers.

42. Safapour, E., Kermanshachi, S., & Nipa, T. J. (2020). Analysis of Cost performance Indicators in Reconstruction Projects: A Comparative Study of Low Vs High Level Damages. In *Creative Construction e-Conference 2020* (pp. 2-10). Budapest University of Technology and Economics.

43. Patel, R. K., Kermanshachi, S., & Namian, M. (2020). A Socioeconomic-Based Analysis of Disaster Preparedness, Awareness and Education. In *Creative Construction e-Conference 2020* (pp. 76-84). Budapest University of Technology and Economics.

44. Patel, R. K., Etminani, R., Kermanshachi, S., & Tafazzoli M. (2022). Exploring Disaster Preparedness and Awareness due to Natural Hazards Using Structural Equation Modelling (SEM). Proceedings of *Construction Research Congress (CRC).*

45. Bostick, T. P., Connelly, E. B., Lambert, J. H., and Linkov, I. (2018). "Resilience science, policy and investment for civil infrastructure." Reliability Engineering & System Safety, 175, 19-23.

46. Rouhanizadeh, B., & Kermanshachi, S. (2021). Gender-Based Evaluation of Economic, Social, and Physical Challenges in Timely Post-Hurricane Recovery. *Progress in Disaster Science* 9(2), 100146.

47. Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual review of ecology and systematics*, *4*(1), 1-23.

48. Pamidimukkala, A., Kermanshachi, S., Adepu, N., & Safapour, E. (2021). Resilience in Water Infrastructures: A Review of Challenges and Adoption Strategies. *Sustainability*, *13*(23), 12986.

49. Rouhanizadeh, B., & Kermanshachi, S. (2020). Gender-Based Evaluation of Physical, Social, and Economic Challenges in Natural Disasters Management. In *Construction Research Congress 2020: Infrastructure Systems and Sustainability* (pp. 865-874). Reston, VA: American Society of Civil Engineers.

50. Nipa, T. J., & Kermanshachi, S. (2021). Dimensions of Resilience Measurement in Critical Transportation Infrastructure. In *International Conference on Transportation and Development 2021* (pp. 302-312).

51. Dick, K., Russell, L., Souley Dosso, Y., Kwamena, F., & Green, J. R. (2019). Deep learning for critical infrastructure resilience. *Journal of Infrastructure Systems*, *25*(2), 05019003.

52. Lam, N. S. N., Qiang, Y., Li, K., Cai, H., Zou, L., & Mihunov#, V. (2018). Extending resilience assessment to dynamic system modeling: perspectives on human dynamics and climate change research. *Journal of Coastal Research*, (85), 1401-1405.

53. Tonn, G., Czajkowski, J., Kunreuther, H., Angotti, K., & Gelman, K. (2020). Measuring Transportation Infrastructure Resilience: Case Study with Amtrak. *Journal of Infrastructure Systems*, *26*(1), 05020001.

54. Hosseini, S., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E: Logistics and Transportation Review*, *125*, 285-307.

55. Redzuan, A. A., Anuar, A. N., Zakaria, R., Aminudin, E., Alias, N. E., Yuzir, M. A. M., & Alzahari, M. R. (2019). A review: Adaptation of escape route for a framework of road disaster resilient. In *IOP Conference Series: Materials Science and Engineering* (Vol. 615, No. 1, p. 012002). IOP Publishing.

56. Fekete, A. (2018). Societal resilience indicator assessment using demographic and infrastructure data at the case of Germany in context to multiple disaster risks. *International journal of disaster risk reduction*, *31*, 203-211.

57. Fraccascia, L., Giannoccaro, I., & Albino, V. (2017). Rethinking resilience in industrial symbiosis: conceptualization and measurements. *Ecological Economics*, *137*, 148-162.

58. Therrien, M. C., Beauregard, S., & Valiquette-L'Heureux, A. (2015). Iterative factors favoring collaboration for interorganizational resilience: The case of the greater montréal transportation infrastructure. *International Journal of Disaster Risk Science*, *6*(1), 75-86.

59. Suárez, M., Gómez-Baggethun, E., Benayas, J., & Tilbury, D. (2016). Towards an urban resilience Index: a case study in 50 Spanish cities. *Sustainability*, *8*(8), 774.

60. Ayyub, B. M. (2014). Systems resilience for multihazard environments: Definition, metrics, and valuation for decision making. *Risk analysis*, *34*(2), 340-355.

61. Nipa, T. J., Kermanshachi, S., & Karthik, S. (2022). Analysis of Investment Decision-Making Factors in Resilience Improvement of Transportation Infrastructures. Proceedings of *Construction Research Congress (CRC).*

62. McDaniels, T., Chang, S., Cole, D., Mikawoz, J., & Longstaff, H. (2008). Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Global Environmental Change*, *18*(2), 310-318.

63. Zhang, W., Wang, N., & Nicholson, C. (2017). Resilience-based post-disaster recovery strategies for road-bridge networks. *Structure and Infrastructure Engineering*, 13(11), 1404-1413.

64. Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., ... & Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake spectra*, *19*(4), 733-752.

65. Sun, W., Bocchini, P., & Davison, B. D. (2020). Resilience metrics and measurement methods for transportation infrastructure: the state of the art. *Sustainable and Resilient Infrastructure*, *5*(3), 168-199.

66. Nipa, T. J., & Kermanshachi, S. (2022). Resilience Measurement in Transportation Infrastructures. *Transportation Research Board 101 Annual Meeting*.

67. Nipa, T. J., Kermanshachi, S., & Patel, R. (2022). Analysis of the Resilience Management Dimensions Based on Project Complexity Level. Proceedings of *Construction Research Congress (CRC).*

68. Nipa, T. J., Kermanshachi, S., & Karthik, S. (2022). Development of Innovative Strategies to Enhance the Resilience of the Critical Infrastructure. Proceedings of *Construction Research Congress (CRC*).

69. Ganin, A. A., Mersky, A. C., Jin, A. S., Kitsak, M., Keisler, J. M., & Linkov, I. (2019). Resilience in intelligent transportation systems (ITS). *Transportation Research Part C: Emerging Technologies*, *100*, 318-329.

70. Safapour, E., & Kermanshachi, S. (2021). Uncertainty analysis of rework predictors in post-hurricane reconstruction of critical transportation infrastructure. *Progress in Disaster Science*, *11*, 100194.

71. Ganin, A. A., Kitsak, M., Marchese, D., Keisler, J. M., Seager, T., & Linkov, I. (2017). Resilience and efficiency in transportation networks. *Science advances*, *3*(12), e1701079.

72. Goidel, K., Horney, J. A., Kellstedt, P. M., Sullivan, E., & Brown, S. E. (2019). Perceptions of disaster resilience in four Texas coastal communities. *Local Government Studies*, *45*(3), 413-432.

73. Li, X., Lam, N., Qiang, Y., Li, K., Yin, L., Liu, S., & Zheng, W. (2016). Measuring county resilience after the 2008 Wenchuan earthquake. *International Journal of Disaster Risk Science*, *7*(4), 393-412.

74. Bešinović, N. (2020). Resilience in railway transport systems: a literature review and research agenda. *Transport Reviews*, *40*(4), 457-478.

75. Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American statistical Association*, *47*(260), 583-621.

76. Rasch, D., Kubinger, K. D., & Moder, K. (2011). The two-sample t test: pre-testing its assumptions does not pay off. *Statistical papers*, *52*(1), 219-231.

77. Franke, T. M., Ho, T., & Christie, C. A. (2012). The chi-square test: Often used and more often misinterpreted. American Journal of Evaluation, 33(3), 448-458.

78. Wilcox, R. (2019). A robust nonparametric measure of effect size based on an analog of Cohen's d, plus inferences about the median of the typical difference. *Journal of Modern Applied Statistical Methods*, *17*(2), 1.

79. Odu, G. O. (2019). Weighting Methods for Multi-criteria Decision-making Technique. *Journal of Applied Sciences and Environmental Management*, *23*(8), 1449-1457.

80. Burton, H., Kang, H., Miles, S., Nejat, A., and Yi, Z. (2019). A framework and case study for integrating household decision-making into post-earthquake recovery models. *International Journal of Disaster Risk Reduction, 37(1), 101167–.* doi:10.1016/j.ijdrr.2019.101167.

81. Wang, W.L. and van de Lindt, J.W. (2021). Quantitative modeling of residential building disaster recovery and effects of pre-and post-event policies. *International Journal of Disaster Risk Reduction*, *59*, p.102259.

82. Niu, Y., Jiang, N. and Jiang, X. (2021). Factors related to the resilience of Tibetan adolescent survivors ten years after the Yushu earthquake. *International Journal of Disaster Risk Reduction*, *65*, p.102554.

83. Song, J., Huang, B. and Li, R. (2017). Measuring recovery to build up metrics of flood resilience based on pollutant discharge data: A case study in East China. *Water*, *9*(8), p.619

84. Waziri, B.S., Bala, K. and Bustani, S.A. (2017). Artificial neural networks in construction engineering and management. *International Journal of Architecture, Engineering and Construction*, *6*(1), pp.50-60.

85. Ghaffarian, S., Kerle, N., Pasolli, E. and Jokar Arsanjani, J. (2019). Post-disaster building database updating using automated deep learning: An integration of pre-disaster OpenStreetMap and multi-temporal satellite data. *Remote sensing*, *11*(20), p.2427.

86. Sheykhmousa, M., Kerle, N., Kuffer, M. and Ghaffarian, S., 2019. Post-disaster recovery assessment with machine learning-derived land cover and land use information. *Remote sensing*, *11*(10), p.1174.

87. Ghaffarian, S. and Emtehani, S. (2021). Monitoring urban deprived areas with remote sensing and machine learning in case of disaster recovery. *Climate*, *9*(4), p.58.

88. Wang, Y. A., and Rhemtulla, M. (2021). Power analysis for parameter estimation in structural equation modeling: A discussion and tutorial. *Advances in Methods and Practices in Psychological Science*, 4(1), 2515245920918253.

89. Zaira, M. M., and Hadikusumo, B. H. (2017). Structural equation model of integrated safety intervention practices affecting the safety behavior of workers in the construction industry. Safety science, 98, 124-135

90. Schumacker, R. E., & Lomax, R. G. (2004). *A beginner's guide to structural equation modeling*. psychology press.

APPENDIX A: INVITATION EMAIL

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).

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: QUESTIONNAIRE

i. <u>Demographic Information</u>

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. <u>Resilience Concept</u>

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. <u>Project-based Resilience Questions</u>

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 material resources 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		