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RESEARCH

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Development of decision-making system measuring the resilience level of highway projects

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Abstract

The recent increase in the frequency and intensity of disasters has damaged and disrupted transportation infrastructures, thereby significantly increasing the economic losses and slowing the pace of recovery. Resilient infrastructures ensure functionality with minimal discontinuity, but there currently exists rarely a tool for assessing the resilience level of existing transportation infrastructures so that the information can be used to make future constructions more resilient. This study aims to identify the significant dimensions for measuring the resilience of transportation infrastructures and to utilize the dimensions to develop a decision-making tool that can be used to assess the level of resilience. A survey supported by a comprehensive literature review was conducted, and statistical tests were performed on the collected data. It was found that network characteristics (length of the link, number of lanes, number of optional routes, etc.), organizational characteristics (time to start reconstruction work, knowledge of the employee, resilience measurement experience, etc.), and information related to data (previous data availability and data accessibility, etc.) have major impacts on the resilience of transportation infrastructures. Based on the impact of statistically significant indicators, a resilience measurement tool was developed that provides a relative resilience score for projects and reveals how each statistically significant dimension affects the resilience. The outcome of this study will help decision-makers and practitioners prioritize their projects for resilience enhancement activities and provide funding accordingly.

Keywords Infrastructure, Transportation, Resilience measurement, Decision-making system, Highway projects

Introduction

The ever-growing global population means that more people are using the services provided by transportation infrastructure systems, and to meet their additional needs and demands transportation infrastructures are becoming costly and complex [19]. Destruction of these complex structures by disastrous events causes both a direct cost that is related to reconstruction and an indirect cost that is related to a decline in the normal economic activities of the affected area [3]. Such costs can be greatly reduced if the structure is resilient enough to experience only minimal damage and normal operations can resume within a short period of time. It is therefore important to know the level of resilience of existing infrastructures so that available funding can be invested wisely in resilience-enhancing activities.

The focus of a traditional recovery is transitioning into a more resilient-based approach for transportation infrastructures [1, 5, 20]. Researchers, as well as national and international organizations, have been emphasizing resilience over recovery in recent years [28] and the concept of resilience is gaining popularity rapidly and being studied vigorously. Resilience ensures that systems can withstand foreseen and unforeseen disasters with minimum

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disruption in their functionality [6, 22, 23], and a system gains resilient characteristics when resilience enhancement activities are introduced. These activities require an investment of time and financial resources, and the limited resources create a dilemma for decision-makers as they select which projects they can restore and renovate [11]. Being able to identify a project's level of resilience and compare it with the outcome will help in identifying critical projects.

The concept of resilience has only been applied to the field of transportation research since 2009 [28], yet it has rapidly become popular and there are a significant number of studies on the subject. The existing literature does not comprehensively measure the level of resilience of the transportation infrastructure due to its complex nature of uncertainty and interconnectivity [26], but there are a limited number of articles that studied the resilience of the transportation infrastructure from construction and management points of view.

Therefore, this study focused on identifying the resilience measurement dimensions and developing a decision-making tool to measure the level of resilience. To fulfill the aim of this study, the following objectives were constructed: (i) determine the factors that potentially affect the level of resilience of transportation infrastructures, (ii) rank and weigh the significant factors, and (iii) develop a resilience-measurement tool. Outcomes of this study will boost decision-makers' confidence in selecting critical transportation infrastructure projects for funding and investment in resilience-enhancing activities.

Literature review

Concept of resilience

Since the conceptualization of resilience by Holling in 1973 in the field of ecology [10], resilience has been researched and explored for more than five decades. Many researchers have used the concept in their respective fields and proposed definitions that are specific to them [7]. A vast number of terminologies are used to define and interpret the concept of resilience, such as McDaniels et al.'s. [16] definition of engineering resilience: robustness and rapidity, in which robustness indicates the level of functionality of the system after it has experienced a disruptive event and rapidity indicates the time required to regain full functionality after a disaster. Zhang et al. [30] used four terminologies to define the resilience of road-bridge networks: robustness (the capability to be functional after a disaster), rapidity (the time required to complete the recovery activities), redundancy (the availability of the alternative elements of the system to be functional), and resourcefulness (the availability of the resources to perform the recovery activities). These four terminologies are known as the 4Rs, and many researchers have used them to explain and define the concept of resilience [2, 23, 26]. According to Labaka et al. [12], a system must have four elements to be considered resilient: technical, organizational, social, and economic resilience, collectively known as TOSE. A system with the ability to provide a sound physical structure to maintain an operation under crisis is technically resilient. A system composed of people who are able to make appropriate and prompt decisions during a crisis is organizationally resilient. A system that has a neighborhood that is educated and prepared to act immediately after a disaster is socially resilient. A system with sufficient funding to recover from a disaster is economically resilient. Systems with these four elements suffer fewer negative consequences after a disaster and will recover more rapidly. The United Nations International Strategy for Disaster Reduction [27] adopted a definition of resilience that does not focus on complex terminologies: the capability of a system to continue its operation at an acceptable level after being attacked by a disaster.

Many definitions of resilience are cited throughout the literature. Reggiani [25] believed that the definition of resilience can be divided into two parts: static and dynamic. The static part denotes the performance level of the system, and the dynamic part denotes the recovery time required for the system to regain a pre-defined performance level after a disaster. Figure 1 illustrates the concept of resilience in different scenarios, using performance as a function of time.

These graphs were developed by taking the performance level along the Y-axis and time along the X-axis. The X-axis also mentions some resilience characteristics of the system. When a system with no capacity for resilience is damaged by a disaster, it faces a total collapse (System 1). If it has a moderate level of resilience, it will eventually regain some level of performance, but usually less than the original capacity (System 2). If a system has solid resilience capacity, it will regain its original level of performance after being affected by a disaster (System 3). Since 2006, researchers and practitioners have been considering the reconstruction phase as an opportunity to build systems back better (Fernandez and Ahmed 2019) so that their level of performance is greater than the original performance level (System 4).

Resilience in the transportation sector

Resilience has only been studied in relation to the transportation sector for two decades, yet there are a significant number of research articles that focus on identifying the dimensions that can measure resilience in transportation infrastructure. The ten dimensions observed in multiple research articles [14, 17, 18] are shown in Table 1.

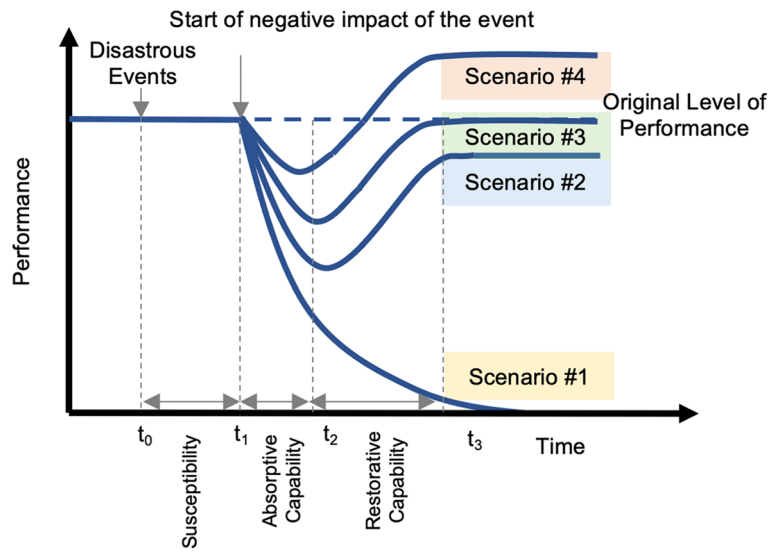

Fig. 1 Graphical representation of resilience

Table 1 Existing Transportation Resilience Dimensions

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

Quantification measures of resilience in transportation infrastructure systems

Despite the rapidly increasing number of researchers who are studying the integration of resilience into transportation infrastructures, the literature fails to provide a universal resilience measurement tool [14]. Murray-Tuite [18] proposed a user equilibrium and system optimum metrics, with adaptability, safety, mobility, and recovery as the dimensions for minimizing travel time. Madni and Jackson [15] proposed a conceptual framework to analyze disruptions and provide principles for building resilient systems based on lessons learned,however, this conceptual technique was not exclusive to transportation infrastructure. Using the infrastructure type and condition, geographical location, the likelihood of disaster, and disaster type as dimensions, Croope and McNeil [4] developed a critical infrastructure resilience decision support system (CIR-DSS) that provides cost–benefit strategies for making the recovery and mitigation phases more efficient. Their model uses the transportation network as an example of critical infrastructure (CIs), but the system is not exclusive to transportation infrastructure and only focuses on the recovery and mitigation phases. Heaslip et al. [9] proposed and Freckleton et al. [8] expanded a conceptual methodology to measure individual resilience, community resilience, economic resilience, and the ability of transportation networks to recover, but it focused on the network's characteristics rather than the physical characteristics of transportation infrastructure. Liao et al. [14] proposed a resilience

optimization model that assumed that the time intervals between the occurrence of a disaster, the maximum damage propagation, gradual recovery, and full recovery are equal,however, the time required to reach these four stages might not always be equal. To conclude, there is no universal agreement on how to quantify transportation resilience [14].

Summary

The above discussions demonstrate that the definition of resilience is specific to each sector, and even researchers from the same sector often have proposed different definitions. It is therefore unsurprising that the literature is unable to provide a universal definition of resilience for 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 deviations after a disaster within a reasonable schedule and budget. To quantify the resilience level of a physical infrastructure in the transportation sector, it is essential to be knowledgeable about the resilience-measuring dimensions. The majority of the above-mentioned dimensions cannot be used to interpret the level of resilience of physical properties of transportation networks; moreover, they focus on traffic behavior rather than characteristics of the road network. Hence, a list of resilience measuring dimensions had to be developed to quantify the resilience of physical characteristics in transportation infrastructures.

Identification of resilience dimensions in transportation infrastructures

After performing a comprehensive review of more than 372 articles in the existing literature on resilience dimensions in transportation infrastructures, Nipa and Kermanshachi [21] realized that the resilience of transportation infrastructure needed to be researched and investigated from the point of view of construction and reconstruction factors. Based on this perspective, they developed a list of 35 dimensions that had the potential to indicate the level of resilience of transportation infrastructures. After performing statistical tests, only 21 of the variables were found to be statistically significant, as shown in Table 2.

The variables were categorized into six groups: structural, construction and management, knowledge and experience, data related, resources, and funding and investment. Table 2 shows that in the structural category seven variables were found to be statistically significant. This signifies that experts believe that the length of a disrupted roadway has a significant impact on the reconstruction process and duration, and therefore, impacts its resilience. The length of the link, number of lanes, number of optional routes, presence of a railroad crossing, remoteness of the project, and distance of the link/node from the affected area also affect the resilience of transportation infrastructures.

Construction and management category has three significant variables (Table 2). The first variable is the time to start reconstruction work. Delay in starting reconstruction work will significantly enhance the recovery cost by increasing indirect cost of disaster. Delay will also prolong the recovery time which indicates possession of low level of resilience by the affected infrastructure. Other two significant variables are ownership of integrated assets and frequency of integration of resilience enhancement activities into the maintenance planning.

Within the knowledge and experience category, there are three significant variables. A decision-maker who is responsible for a roadway network and is familiar with the concept of resilience is willing to take the initiative to increase the resilience level of the infrastructure and to invest in resilience enhancement activities. Hence, providing a platform that educates users about the concept of resilience and how to measure it would be beneficial. Quantifying and monitoring the resilience level of an infrastructure on a regular basis will facilitate the implementation of effective practices on roadways with low resilience levels.

In the data related category, there are two significant variables, both of which are related to historical data that enables sound predictions of future disaster risks and helps in assessing probable related damages. Such activities would make it possible to initiate preventive measures that would reduce the cost of restorative activities after a disaster.

In the category resources, there are two significant variables – the availability of and access to resources. First responders are literally life savers in the aftermath of a disaster, and the availability of emergency response equipment, such as that used to remove debris, makes it possible for them to perform their jobs. Storing emergency resources in an easily accessible place would enable them to act more quickly and more efficiently.

For the funding and investment category of resilience measurement dimensions, four significant variables were found (Table 2). Timely authorization of funding to resilience enhancement activities would ensure that the infrastructure has the capacity to absorb the negative impact of a disaster and bounce back to a satisfactory level of operation within a short period. An investment in resilience activities should be considered whenever a new project is being planned.

Table 2 Proposed dimensions for measuring the resilience of transportation infrastructure systems (adapted from Nipa and Kermanshachi 2022 [21])

Category	#	Resilience Dimensions
Structural Category	1	Number of nodes
	2	Length of the disrupted roadway
	3	Length of the link
	4	Number of lanes
	5	Number of optional routes
	6	Emergency nodes
	7	Presence of a railroad crossing
	8	Distance of the link/node from the affected area
	9	Remoteness of the project
Construction and Management Category	10	Time to start reconstruction works
	11	Information dissemination
	12	Periodical review system for emergency resources
	13	Ownership of integrated infrastructure assets
	14	Frequency of integration of resilience enhancing activities into maintenance planning
Knowledge and Experience category	15	Educational platform on resilience for infrastructure
	16	Company employees' knowledge of resilience
	17	Previous disaster experience
	18	Project manager who is informed about emergency resources
	19	Frequency of evaluation of resilience in the project
	20	Level of damage
Data Related	21	Availability of previous disaster data for the roadway
	22	Access to previous disaster data for the roadway
	23	Database of historical resilience=enhancement activities and their associated costs
Resources Category	24	Availability of emergency response equipment
	25	Storing resources
	26	Accessibility to non-machinery resources (humans and materials)
	27	Shortage of human resources
	28	Shortage of material resources
Funding and Investment	29	Availability of funding
	30	Regular funding for resilience-enhancement activities
	31	Time of allocation of funding
	32	Considering resilience as part of the investment decision-making process
	33	Involvement in the investment decision-making process
	34	Resilience investment in new projects
	35	Frequency of investing in resilience-enhancing activities

N.B. Significant variables are highlighted

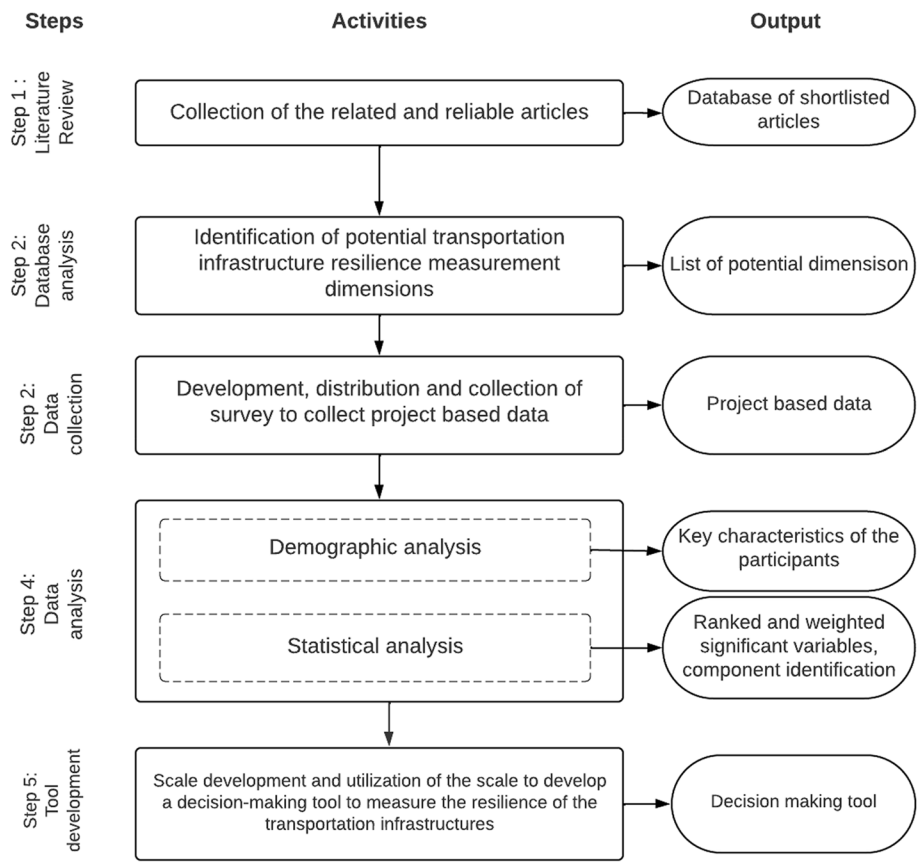

Fig. 2 Research methodology

Methodology

Research outline

Figure 2 shows the five-step methodology that was adopted to fulfill the purpose of this study. A comprehensive literature review was conducted in the first step to determine what the literature has to say about the resilience of transportation infrastructure projects. Resilience is a relatively new term for the field of transportation, hence the years from 2000 to the present day were the focus. A preliminary search resulted in 600 articles. Of them, 372 articles were shortlisted based on the scope of the study and 109 of them were related to resilience in transportation infrastructures. The second step focused on utilizing the shortlisted articles to develop a database, and in the third step, a survey was developed to collect project-based information from participants experienced with transportation construction and/or reconstruction projects. The survey was pilot tested and was reviewed by the Institutional Review Board (IRB) of the University of Texas at Arlington for appropriateness and was sent to targeted participants through electronic media. After multiple follow-up emails, 92 valid responses were collected. Demographic data collected from the survey showed the key characteristics of the participants. Multiple statistical tests were performed on the collected data to rank and weight significant variables, and a decision-making tool was developed, based on the weighted variables.

Data collection

Related and reliable resources including journal papers, conference proceedings, dissertations and theses, and research reports were collected by entering keywords into search engines like Google Scholar, Web of Science, JSTOR, Science Direct, ProQuest, and SciFinder. Examples of the keywords used are: resilience, resilience system, disaster resilience, resilience indicator, resilience index, resilience measurement, resilience measuring framework, and resilience in the transportation system. Resilience has been analyzed for more than 50 years; however, to be practical and to match the scope of the study, only articles published after the year 2000 were focused upon. Initially, 600 articles were collected, but based on the study of the abstracts, 372 articles were short-listed for systematic

content analysis. Content analysis was performed in two stages. In the first stage, the articles were analyzed and the relevant information was recorded in a tabular form that served as the framework for the database. The second stage involved shortlisting the articles that were most applicable to this research. A total of 109 articles that pertained to transportation engineering were shortlisted, each was studied thoroughly, and pertinent information was collected and stored in the database. A survey was developed to collect project-based information.

The survey consisted of 43 questions that were divided into five sections: demographic, project-based, resilience-based, resilience dimensions-based, and best practices-related questions. The survey was pilot tested to verify its appropriateness for the targeted participants and was reviewed by the Institutional Review Board (IRB) of the University of Texas at Arlington to protect the rights and welfare of the human subjects. After addressing modifications suggested by committee members of the IRB, the survey was approved for distribution and was sent to potential participants through electronic media, QuestionPro in July 2021. Since the study required the opinions of experts who had experience working in the field of transportation infrastructures, it was distributed to the people who had an affiliation with the departments of transportation (DOTs); Federal Highway Administration (FHWA); state transportation agencies (STAs); and metropolitan planning organizations (MPOs) like North Central Texas Council of Governments (NCTCOG), etc. After a couple of reminder emails, 92 fully and significantly completed responses were received.

Descriptive data analysis

Participants' demographic information

The goal of the research team was to collect project-based information from experts employed by state, national, and international transportation agencies. Figure 3a shows that 53% of the projects were handled by city and/or county transportation agencies, 27% were handled by state DOTs, and 9% were handled by the Federal Highway Administration (FHWA). Figure 3b shows that 32% of the participants were in supervisory positions, including director, deputy director, program supervisor, etc.; 23% were in managerial positions such as project manager, program manager, engineer manager, etc. Project engineers, city engineers, area engineers, and traffic engineers were among those from engineering departments; the rest of the participants were from analysis and planning departments, administrative departments, safety, and inspection departments, etc. Figure 3c shows the number of years that the participants had worked in their field; 60% of them had worked in the field of transportation for more than 20 years. Figure 3d shows that 73% of the participants had been involved in a reconstruction project necessitated by a natural disaster. Even though most of the participants were highly experienced in construction and reconstruction works, only 45% were very familiar with the concept of resilience in transportation infrastructures.

Statistical data analysis

Statistical tests to be performed

Cohen's d method

Cohen's d method can measure the effect size of two independent groups by identifying the standardized mean difference between them. The following equation is used to determine Cohen's d values [29]. A small, medium, and large effect indicate Cohen's d value of < 0.2, 0.5, and > 0.8 respectively [13].

$$d = \frac{\overline{X}_1 - \overline{X}_2}{S} \tag{1}$$

$$S^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{2}$$

where,

X_1 and X_2 are two independent variables, n is the sample size, and s is the standard deviation.

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

Rank-sum method

The rank-sum method is used to determine the weight of a variable corresponding to a list of ranked variables [24]. To obtain the weight of each variable, its corresponding score is initially calculated and assigned using Eq. 3. The weight of the variables was assigned using Eq. 4.

$$S_i = N - R_i 1 \tag{3}$$

$$W_i = \frac{S_T}{\sum_{j=1}^{N} S_j} \tag{4}$$

where,

N is the number of variables.

R_i is the rank of the i-th variable.

Wi is the weight, and.

S_T is the score associated with each variable.

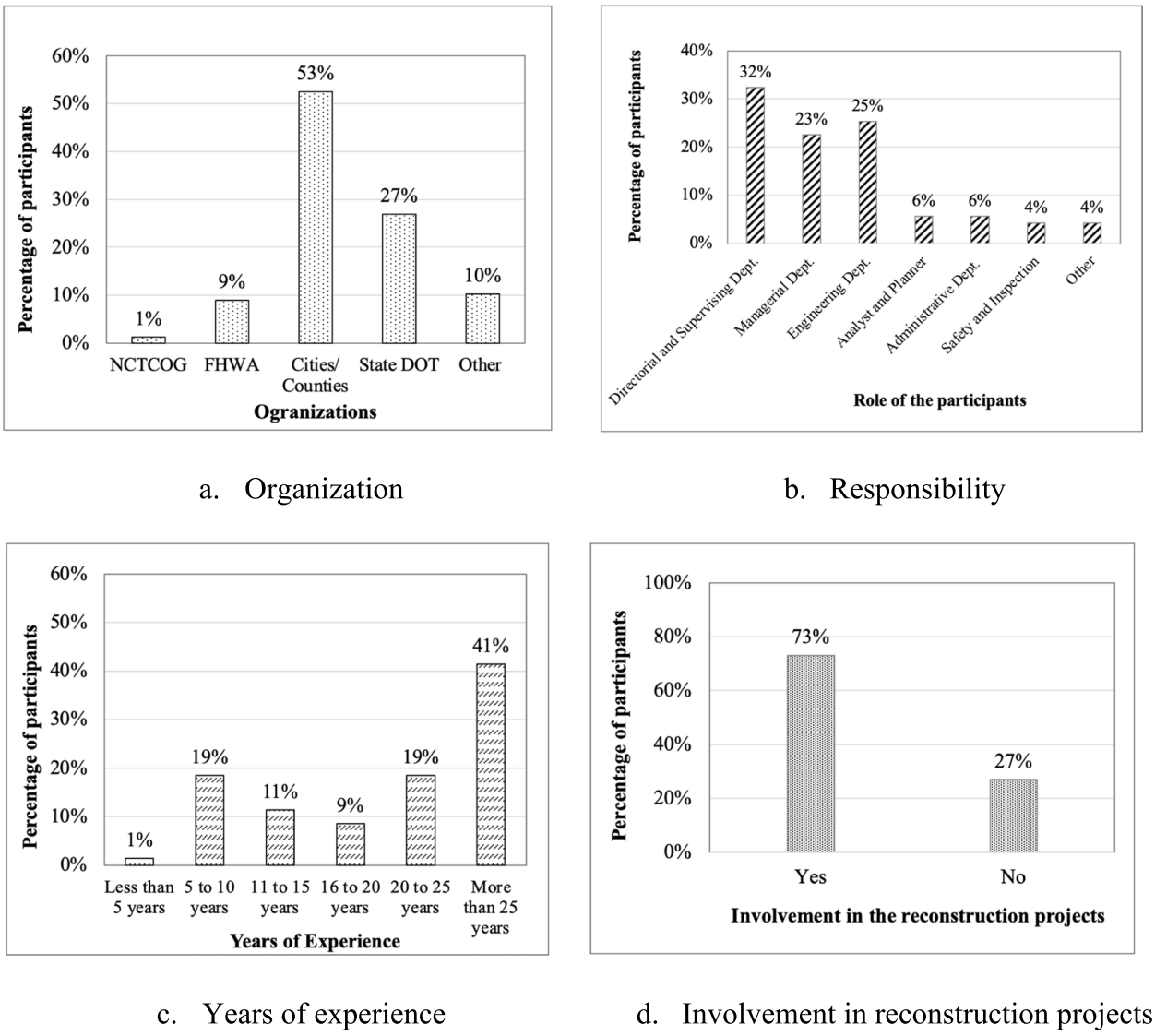

Fig. 3 Distribution of participants based on demographic information

Ranking and weighing of significant variables

Various factors make transportation infrastructure projects vulnerable at different levels and not all variables have the same degree of effect on their resilience. The p-values from statistical tests informs about whether there exists an effect or not, however they did not include the size of the effect. Therefore, Cohen's d method was used to determine the effect size of the 21 variables that were deemed significant, as shown in Table 3. The raw data from the survey is utilized and Cohen's d method is performed in SPSS V 27.0. According to Cohen's d value, the total length of a disrupted roadway has a moderate effect on the resilience level; the length of the link has a large effect. Based on Cohen's d value, the factors were grouped as small, medium and large. However, it is important to differentiate the variables within the categories small, medium, and large.

Cohen's d values were normalized into corresponding ratios to rank the resilience measurement dimensions from those that have the greatest impact on the resilience level of transportation infrastructures to those that have the least impact. The normalized Cohen's d values were calculated according to the result of effect size associated with each dimension, divided by the summation of all the results of effect size. The normalized values are shown in Table 4.

As presented in the Table 4, after the Cohen's d value were normalized, the variables were ranked from 1,

Table 3 Determination of the effect size of the variables

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

Table 4 Universal ranking and weighing of variables

#	Dimensions	Normalized Cohen's d value	Rank	Score	Weight
2	Length of the disrupted roadway	0.0339	16	6	0.026
3	Length of the link	0.0649	4	18	0.0779
4	Number of lanes	0.0523	10	12	0.0519
5	Number of optional routes	0.0612	5	17	0.0736
7	Presence of a railroad crossing	0.0525	9	13	0.0563
8	Distance of the link/node from the affected area	0.0045	21	1	0.0043
9	Remoteness of the project	0.0449	15	7	0.0303
10	Time to start reconstruction works	0.0657	3	19	0.0823
13	Ownership of integrated infrastructure assets	0.0554	7	15	0.0649
14	Frequency of integration of resilience-enhancing activities into maintenance planning	0.0214	20	2	0.0087
15	Educational platform on resilience for infrastructure	0.0218	19	3	0.013
16	Company employees' knowledge of resilience	0.0480	13	9	0.039
19	Frequency of evaluation of resilience in the project	0.0224	18	4	0.0173
21	Availability of previous disaster data for the roadway	0.0757	2	20	0.0866
22	Access to previous disaster data for the roadway	0.0601	6	16	0.0693
24	Availability of emergency response equipment	0.0552	8	14	0.0606
26	Accessibility to non-machinery resources (human and material)	0.0281	17	5	0.0216
30	Regular funding for resilience-enhancement activities	0.0499	11	11	0.0476
31	Time of allocation of funding	0.0499	12	10	0.0433
34	Resilience investment in new projects	0.0859	1	21	0.0909
35	Frequency of investing in resilience-enhancing activities	0.0463	14	8	0.0346

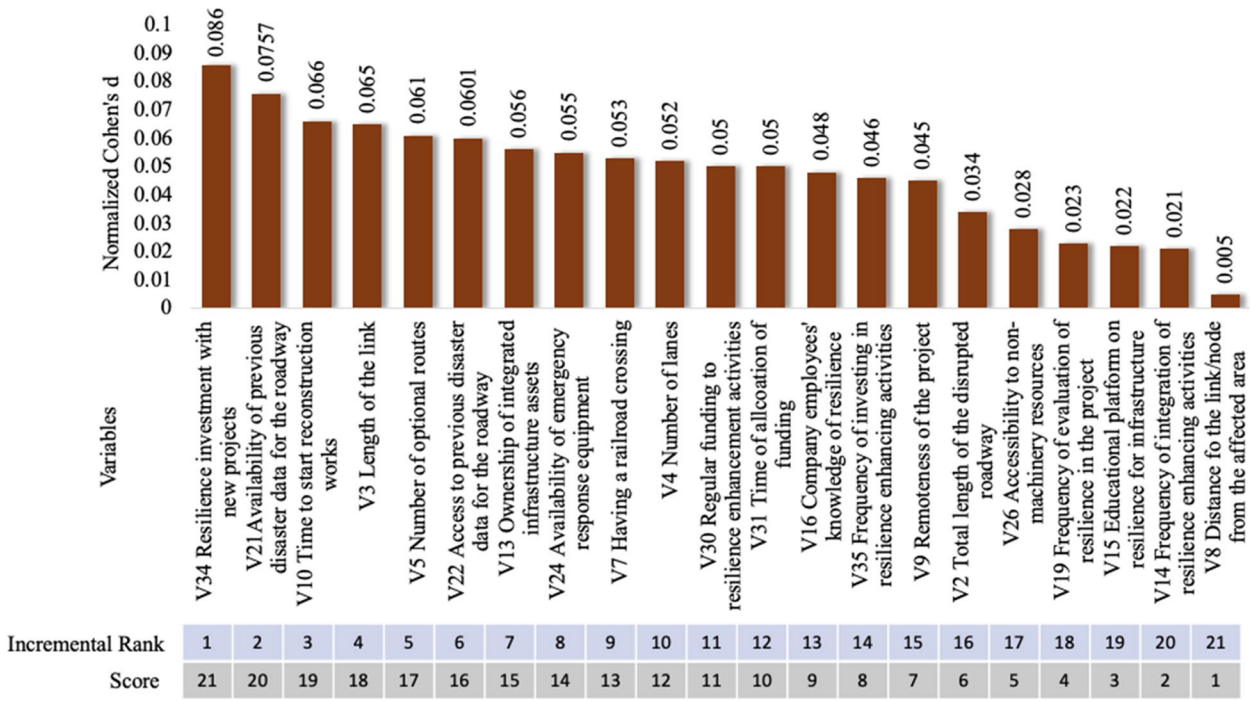

Fig. 4 Incremental ranking and scoring of variables

indicating the variable with the highest effect size, to 21, indicating the variable with the lowest effect size Variable 34, resilience investment in new projects, had the highest normalized effect size (0.086); variable 21, the availability of previous disaster data for the roadway, had the second highest normalized effect size (0.075).

The ranked variables were organized incrementally, and the rank-sum method was applied. Figure 4 illustrates how the variables were arranged based on their incremental rank; each variable was given a score appropriate with its rank.

Because the effects of the factors on the resilience of the transportation infrastructures are not equally distributed, it was necessary to determine the weights of the resilience measurement dimensions. Table 4 displays the results of the rank-sum method, where the number 1 ranked variable, resilience investment in new projects, had a maximum weight of 0.0909. This value illustrates that a roughly 9% difference in resilience levels will occur if no investment is made in resilience activities in the planning stages. The second-highest weighted dimension, the importance of previous disaster data for the roadway, has a weight of 0.087. The effects of other variables can be explained based on their weights.

Development of the decision-making Tool

Development of the scale

To fulfill the aims of this study, ranked and weighted resilience dimensions were used to develop a decision-support tool that can be used to measure the relative resilience of transportation infrastructures. The tool was designed to have a comprehensive scale so that the user can choose the option that will best resonate with the level of resilience of the infrastructure.

Each dimension was scaled based on three definitions: rarely, often, and regular. For example, the first variable, resilience investment in new projects, indicates when a resilience investment is authorized for new projects. Each measure was scaled according to three scores: 1–3 for the first measure, 4–6 for the second measure, and 7–9 for the third measure. To summarize, each dimension was defined in three measures and scored from 1–9, with 1 indicating that it has the least impact on resilience and 9 indicating that it has the greatest impact. All 21 variables were defined accordingly, as shown in Fig. 5.

Calculating resilience using the tool

Figure 6 displays a resilience measurement matrix that can be used to collect the user's inputs. Users have the option to score each resilience measurement dimension

#	Dimensions		Score			Score selection	Comments
1	Resilience investment with new projects	Scale	Never 1 2 3	Sometime 4 5 6	7 8 Always 9		
		Measure	Rarely	Often time	Regular		
2	Availability of previous disaster data for the roadway	Scale	None 1 2 3	Medium 4 5 6	7 8 High 9		
		Measure	Limited data availability	Just enough data were available	Data were recorded elaborately		
3	Time to start reconstruction works	Scale	Long 1 2 3	Medium 4 5 6	7 8 Short 9		
		Measure	After a long time	After a while	Immediate		
4	Length of the link	Scale	Long 1 2 3	Medium 4 5 6	7 8 Short 9		
		Measure	Long length	Medium length	Short length		
6 - - - - 19	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -		
0	Frequency of integration of resilience enhancing activities into the maintenance planning	Scale	Low 1 2 3	Medium 4 5 6	7 8 High 9		
		Measure	Not often	Seldom	Regular		
21	Distance of the link/node from the affected area	Scale	Low 1 2 3	Medium 4 5 6	7 8 High 9		
		Measure	In the affected area	Outside the affected area	Far from the affected area		

Fig. 5 Resilience measurement matrix

from 1 to 9, based on the characteristics of the project. If a dimension is not related to a particular project, the N/A option may be selected, which will establish a score of zero for that variable. Additionally, users will have the option to provide comments and/or additional information corresponding to resilience dimensions.

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

$$\textit{Resilience impact value of the variable} = \textit{Weight of the dimension} * \textit{Score of the dimension} \tag{5}$$

$$\textit{Level of resilience of the transportation infrastructure} = \sum_{\textit{Variable}\,1}^{\textit{Variable}\,21} \textit{Resileince impact value of the dimension} \tag{6}$$

Figure 6 shows the output window of the decision-making tool. The user will enter the score in the column named "Score Selection," then the resilience impact value will be calculated using Eq. 6. The last row shows

#	Resilience Dimensions	Weights	Project 1	
			Score selection	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) =				

Fig. 6 Resilience measurement output

the level of resilience of the transportation infrastructure network, which is calculated by totaling the resilience impact values. This tool can be utilized for a variety of projects and will assist those responsible for decisions in making sound judgments by comparing level of resilience of the projects.

Conclusion

The objectives of this study were to identify resilience measurement dimensions for transportation infrastructures and develop a decision-making tool that could measure their level of resilience. After conducting a comprehensive literature review of more than 372 scholarly articles, potential resilience measurement dimensions were identified that served as the basis for a survey that was developed and distributed among experts in the construction and maintenance of transportation infrastructures. A demographic data analysis of the survey results showed that even though 73% of the participants were involved in transportation infrastructure reconstruction and 60% of the participants had more than 20 years of experience in such efforts, only 45% of the participants were familiar with the concept of resilience in transportation. Statistical tests were performed to rank and weigh the resilience enhancement dimensions, and a decision-making tool was developed that provides a relative resilience score for different projects and shows how each statistically significant dimension affects their overall resilience. This model will help practitioners make informed investment decisions and enable them to prioritize available funding allocations in ways that will enhance the resilience of transportation infrastructure.

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Authors' contributions
Conceptualization, T.J.N., and S.K; methodology, T.J.N., S.K., and A.P; writing—original draft preparation, T.J.N., A.P; writing—review and editing, T.J.N., S.K., and A.P; supervision, S.K. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

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References

1. Brummitt CD, D'Souza RM, Leicht EA (2012) Suppressing cascades of load in interdependent networks. Proc Natl Acad Sci 109(12):E680–E689
2. Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace W, Winterfeldt VD (2003) A framework to quantitatively assess and enhance the seismic resilience of communities. Earthq Spectra 19(4):733–752
3. Cox A, Prager F, Rose A (2011) Transportation security and the role of resilience: A foundation for operational metrics. Transp Policy 18(2):307–317
4. Croope SV, McNeil S (2011) Improving resilience of critical infrastructure systems post disaster: recovery and mitigation. Transp Res Rec 2234(1):3–13
5. Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008) A place-based model for understanding community resilience to natural disasters. Glob Environ Chang 18(4):598–606
6. Dick K, Russell L, Souley Dosso Y, Kwamena F, Green JR (2019) Deep learning for critical infrastructure resilience. J Infrastruct Syst 25(2):05019003
7. Franchin P, Cavalieri F (2015) Probabilistic assessment of civil infrastructure resilience to earthquakes. Computer-Aided Civil and Infrastructure Engineering 30(7):583–600
8. Freckleton D, Heaslip K, Louisell W, Collura J (2012) Evaluation of resiliency of transportation networks after disasters. Transp Res Rec 2284(1):109–116
9. Heaslip K, Louisell W, Collura J (2009) A methodology to evaluate transportation resiliency for regional networks. Transportation Research Board 88th annual meeting, Washington D.C, United States (No. 09-3194).
10. Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 4(1):1–23
11. Kong J, Zhang C, Simonovic SP (2019) A two-stage restoration resource allocation model for enhancing the resilience of interdependent infrastructure systems. Sustainability 11(19):5143
12. Labaka L, Hernantes J, Sarriegi JM (2016) A holistic framework for building critical infrastructure resilience. Technol Forecast Soc Chang 103:21–33
13. Larner AJ (2014) Effect size (Cohen's d) of cognitive screening instruments examined in pragmatic diagnostic accuracy studies. Dementia and Geriatric Cognitive Disorders Extra 4(2):236–241
14. Liao TY, Hu TY, Ko YN (2018) A resilience optimization model for transportation networks under disasters. Nat Hazards 93(1):469–489
15. Madni AM, Jackson S (2009) Towards a conceptual framework for resilience engineering. IEEE Syst J 3(2):181–191
16. 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. Glob Environ Chang 18(2):310–318
17. Moteff JD (2012) Critical infrastructure resilience: the evolution of policy and programs and issues for congress
18. Murray-tuite PM (2006) A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions, Proceedings of the 2006 Winter Simulation Conference, Monterey, CA, USA, pp. 1398-1405, https://doi.org/10.1109/WSC.2006.323240
19. Nipa TJ, Kermanshachi S Ramaji I (2019) Comparative analysis of strengths and limitations of infrastructure resilience measurement methods. In 7th CSCE International Construction Specialty Conference (ICSC) 2019. Canadian Society of Civil Engineers, Laval, Greater Montreal, pp. 292 (1-10)
20. Nipa TJ, Kermanshachi S (2020) Identification of the resilience dimensions and determination of their relationships in critical transportation infrastructure. Construction Research Congress 2020: Infrastructure Systems and Sustainability. American Society of Civil Engineers, Reston, VA, pp 644–653
21. Nipa TJ, Kermanshachi S (2022) Resilience measurement in highway and roadway infrastructures: Experts' perspectives. Progress in Disaster Science. https://doi.org/10.1016/j.pdisas.2022.100230
22. Nipa TJ, Kermanshachi S, Pamidimukkala A (2023) Identification of Resilience Dimensions in Critical Transportation Infrastructure Networks. J Leg Aff Disput Resolut Eng Constr 15(2):03122001
23. Nipa TJ, Kermanshachi S, Pamidimukkala A (2023) Evaluation of Resilience Dimensions on Reconstruction of Highway Infrastructure Projects. J Leg Aff Disput Resolut Eng Constr 15(2):04522057
24. Odu GO (2019) Weighting methods for multi-criteria decision-making technique. J Appl Sci Environ Manag 23(8):1449–1457
25. Reggiani A (2013) Network resilience for transport security: Some methodological considerations. Transp Policy 28:63–68
26. Sun W, Bocchini P, Davison BD (2020) Resilience metrics and measurement methods for transportation infrastructure: the state of the art. Sustainable and Resilient Infrastructure 5(3):168–199
27. UNISDR (2007) Hyogo framework for action 2005–2015: building the resilience of nations and communities to disasters. United Nations International Strategy for Disaster Reduction, Geneva
28. Wan C, Yang Z, Zhang D, Yan X, Fan S (2018) Resilience in transportation systems: a systematic review and future directions. Transp Rev 38(4):479–498
29. 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. J Mod Appl Stat Methods 17(2):1
30. Zhang W, Wang N, Nicholson C (2017) Resilience-based post-disaster recovery strategies for road-bridge networks. Struct Infrastruct Eng 13(11):1404–1413

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