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Defining Transportation Systems Resilience under Natural Disasters: A Bibliometric Analysis Based on Mode, Metrics and Scope

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Abstract

Climate change is causing changes in the distribution of natural disasters in countries. Major disaster relief plans rely on the availability of transportation systems during disasters; however, transportation systems (road, rail, air, etc.) are also vulnerable to disruptions of natural disasters such as hurricanes, floods, etc. While each disaster may cause a different type of disruption to a transportation network (flooding, road closures, facility failures, etc.), each transportation system also has a different resilience to a disaster. For example, air services may not be available during a hurricane but may be available during an earthquake. Thus, it is necessary to define "transportation systems resilience", which is the aim of this study. To derive the necessary resilience parameters for different transportation systems, a bibliometric analysis was performed using Bibliometrix on literature search results of 3350 abstracts from the Web of Science (WoS) database using the keywords "resilience" and "transport". Reviewed articles were classified based on a) transportation systems, b) disaster types, and c) resilience index types. Descriptive and visual evaluation of the bibliometric analysis showed that there has been a growing interest in the topic since 2010, with an exponential increase. A further selection of 279 studies using title-based search allowed a more detailed analysis; the results showed that resilience measurement parameters can vary significantly between transportation systems. The resilience index definition is not straightforward for transportation systems; it is necessary to clarify the resilience scope, including the vulnerability of critical transportation infrastructures (bridges, airports, etc.), as well as accessibility to and within a disaster region. Transportation system resilience must be defined in a multi-scale (city, intercity, national, etc.) and multi-hazard (floods, hurricanes, etc.) scope for a region, where the vulnerability of different transportation systems needs to be evaluated separately to estimate the total resilience in the region.

Keywords: Resilience; Transportation system; Vulnerability; Measurement

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1. Introduction

Climate change poses environmental threats and causes changes in the distribution of natural disasters in many countries, which must be addressed appropriately. During these disasters created by escalation in extreme weather conditions (i.e. ranging from heavier rainfall and stronger winds to floods, droughts, and wildfires), transportation systems are critical, as they provide necessary lifelines and serve crucial tasks such as evacuations, emergency responses, and search and rescue (S&R) operations. However, despite their essential roles, transportation systems are among the critical infrastructures susceptible to substantial damage. For instance, Hurricane Harvey in 2017 led to extensive flooding and infrastructure damage in Houston, TX, USA, compromising emergency responses and underscoring the necessity for resilient infrastructure (Safapour and Kermanshachi, 2021). Similarly, the floods in Western Europe in July 2021 severely disrupted transportation networks, especially in Germany; it caused considerable damage to the railroad infrastructure and highlighted similar resilience needs (Szymczak et al., 2022). More recently, the twin earthquakes in Türkiye on February 6, 2023, with magnitudes of 7.7 and 7.6, severely impacted transportation infrastructures and hindered critical relief efforts (Yılmaz et al., 2023).

The importance of transportation networks in disaster response brought up the concept of “resilience within transportation systems”, which has captured the interest of various scientific disciplines in recent years and led to significant growth in literature. However, variability in terminologies, models, and metrics used in different research fields has created a dispersed literature landscape and posed a challenge for readers. This study aims to address different aspects of transportation systems resilience and identify key parameters via a comprehensive analysis of large bibliometric datasets. The results are expected to contribute to developing a more generalized and integrated framework for the field of transport systems resilience.

2. Methodology

The bibliometric analysis focused on quantitative evaluation of the literature on the resilience of transportation systems, following the main steps of data collection, screening, and analysis (see Fig. 1). The data were extracted from the Web of Science (WoS) database over two consecutive days (May 20 and 21, 2023) with advanced search queries using the keywords “resilient”, “transportation”, “network”, and “system”. The initial abstract-based search yielded an extensive data set of 3350 documents, within which a refined subset of data with 279 documents was selected via title-based search. The two bibliographic datasets were studied using the bibliometrix tool in R. As Aria and Cuccurullo (2017) stated that this tool offers both descriptive and graphical capabilities for data analysis. The descriptive analysis included regression to assess growth trends and evaluations of the most influential journals in this domain. For the visual evaluation, thematic and network maps were generated with keyword co-occurrences to identify the trends and research patterns. Filtering the title-based dataset based on abstract screening resulted in 115 studies directly related to resilience in transportation systems, which were later subjected to an in-depth analysis that included categorization and clustering by transportation mode and disaster type. This analysis allowed for identifying the clustering of the perspectives used for definitions, contexts, and measurement methodologies. This approach facilitated the emergence of definition clusters, providing an understanding of resilience in transportation systems.

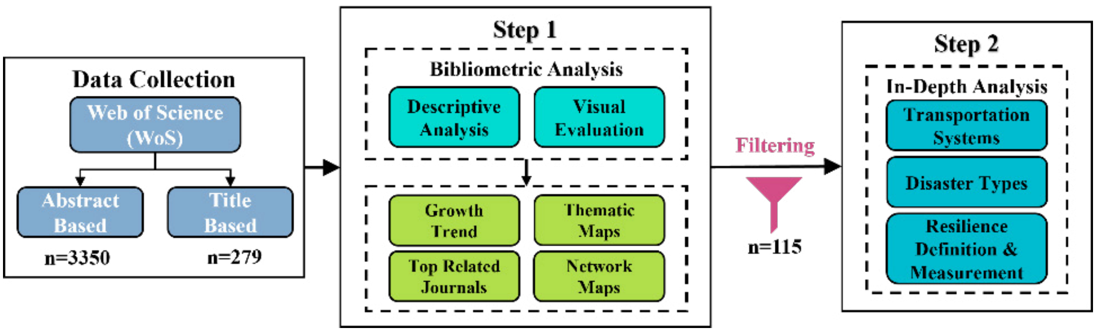

Fig. 1. Analysis framework.

3. Results

3.1. Descriptive Analysis

The temporal distribution of publications based on years for both abstract-based and title-based datasets was assessed and illustrated in Fig. 2. The cumulative number of studies, spanning from 1997 to 2022, was best characterized by an exponential growth trend. Regression coefficients above 0.99 for both datasets indicate a robust upward trajectory in research volume. The year 2006 is particularly noteworthy as it marks the beginning of this pronounced upturn, with the 2010s experiencing a significant surge in scholarly interest. The adoption of the Hyogo Framework for Action 2005-2015 (UN-ISDR, 2007) by the international community can be seen as the cause of this increase in interest, as this initiative aimed to build resilience to natural disasters. The subsequent increase aligns with major global events and policy shifts that have underscored the importance of resilient infrastructure.

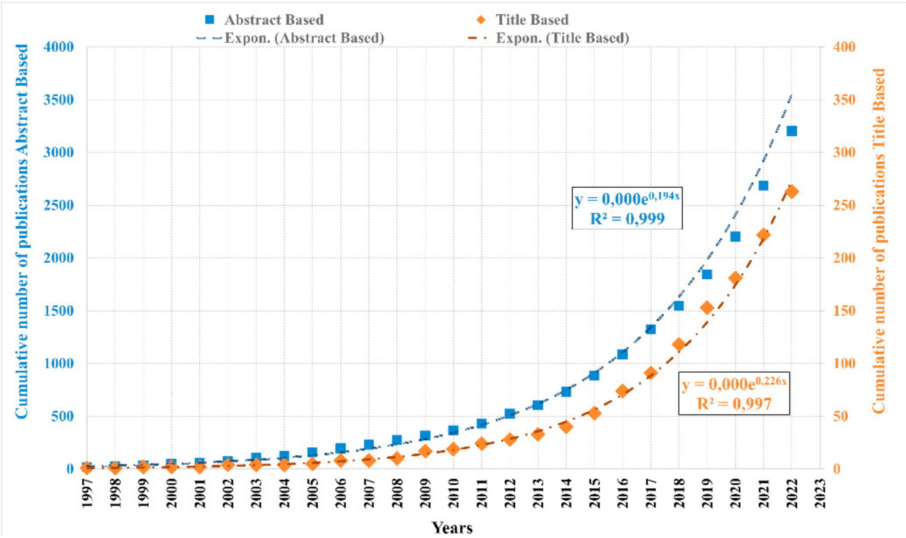

Fig. 2. Cumulative number of publications according to abstract and title-based searches.

The examination of the number of research articles and critical journals contributing to the field is presented in Table 1. Based on abstract-based search data, the most productive source on resilient transportation is “Sustainability”, a multidisciplinary journal covering sustainable development and environmental management topics. In contrast, “Transportation Research Record” emerged as the leading journal based on title-based search result data, reflecting its comprehensive coverage of transportation research and policy, including planning, design, operations, and management aspects. The journal “Reliability Engineering & System Safety” stands out in both searches, reflecting the interdisciplinary nature of transportation systems resilience, which intersects with environmental management, engineering, and policymaking.

Table 1. The top 10 journals according to the number of related published articles.

Rank	Name of Journals	Title Based	Abstract Based
1	**Transportation Research Record**	**16**	**68**
2	**Reliability Engineering & System Safety**	**15**	**43**
3	**Sustainability**	**9**	**77**
4	Transportation Research Part D-Transport and Environment	6	28
5	IEEE Transactions on Intelligent Transportation Systems	6	20
6	Transport Policy	5	23
7	International Journal of Critical Infrastructures	4	9
8	International Journal of Disaster Risk Reduction	3	29
9	Sustainable Cities and Society	3	27
10	IEEE Access	3	20

3.2. Visual Evaluations

The visual evaluation aspect of the analysis by the bibliometrix tool categorized key terms into four themes: i) motor (driving forces of the field), ii) basic theme (foundational elements), iii) emerging/declining, and iv) niche, which is repeated twice for a) abstract-based and b) title-based datasets (see Fig. 3). In both thematic maps, “vulnerability” is a basic theme frequently associated with terms like “sustainability”, “reliability”, and “robustness”. “Climate change” emerges as a motor theme, closely linked with “resilience”, “critical infrastructure,” and “transportation network,” demonstrating its pivotal role in the literature. Differences arise in the emphasis of specific themes: “infrastructure” and “recovery” are more pronounced in the abstract-based map, while “network” and “planning” gain greater prominence in the title-based map, suggesting a shift towards more concrete, operational aspects in titles. Niche themes, such as “machine learning” in the abstract-based and “cybersecurity” in the title-based maps, point to the field’s evolution, with technological innovation becoming increasingly relevant. This contrast underscores a broader thematic scope within abstracts and a more concentrated focus on titles. These maps demonstrate the complexity and dynamic nature of “resilience” as a research topic within transportation systems.

The network maps illustrated the co-occurrence of author keywords are visualized in Fig. 4. In the abstract-based map (part a), five main clusters were identified with the themes of “resilience”, “climate change”, “sustainability”, “covid-19”, and “security”. Notably, “vulnerability” frequently co-occurs with “resilience”, forming a central cluster indicative of their strong association within the literature. However, the title-based map (part b) displayed a more condensed thematic structure, with three main clusters: “resilience”, “vulnerability”, and “robustness”. The distinct clustering of “vulnerability” and “resilience” suggests a differentiation in how these terms are contextually applied, emphasizing their interrelated yet distinct roles in the field.

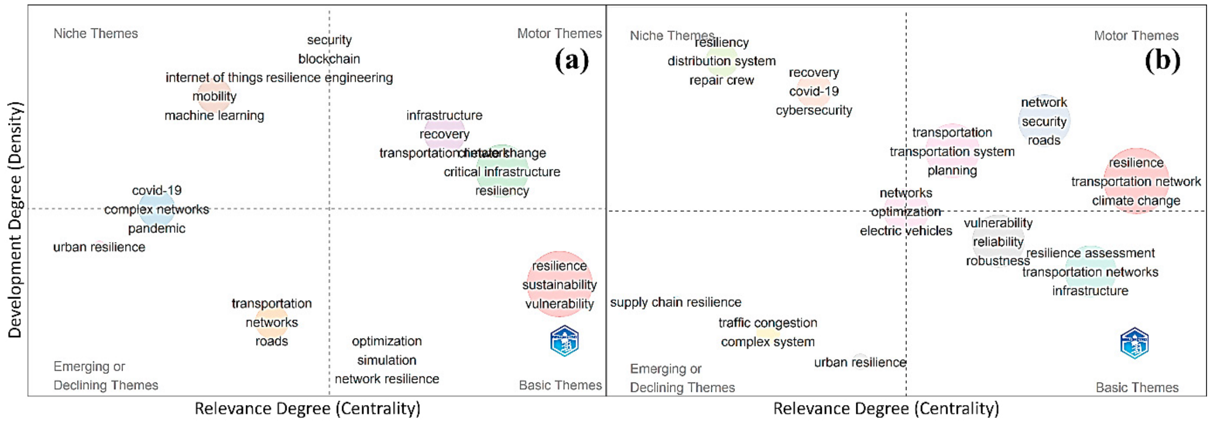

Fig. 3. Thematic maps of authors’ keywords: a) abstract-based b) title-based.

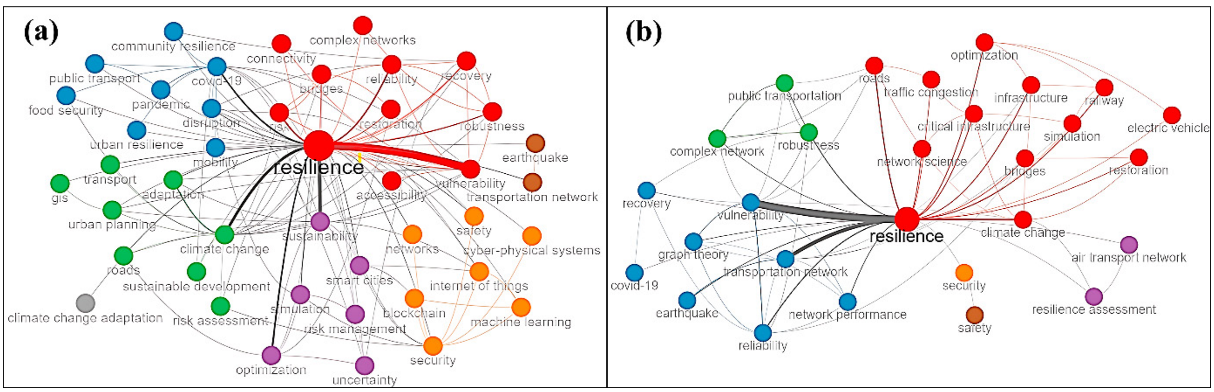

Fig. 4. Network map visualization of author keywords a) abstract-based search b) title-based search.

3.3. In-Depth Analysis

In 115 studies selected based on their abstracts, in-depth review results revealed a significant emphasis on road networks (see Table 2). A total of 41.8% of the studies focused on road transportation resilience. They mostly addressed problems of highways and urban roads, and introduced road network assessment approaches and resilience indices, as in Tang et al. (2019) and Nogal and O'Connor (2018). Urban rail systems represented 7.1% of the studies, highlighting the interdependencies between bus and metro systems, and their impact on urban transport resilience, as addressed by Chen et al. (2023). Similarly, Miller-Hooks et al. (2012) discussed resilience strategies for rail freight transportation, particularly its capacity to handle disruptions and recovery mechanisms. In air transportation resilience, Baspinar et al. (2021) discussed operational challenges at airports during crises and presented metrics for resilience evaluation. While studying the resilience of maritime transport, which is critical for global trade, Dui et al. (2021) underscored the impact of political and natural disruptions. Additionally, the review highlighted the growing interest in integrated and intermodal transport systems, accounting for about 21.9% of the studies; Baggag et al. (2018) advocated for multiplex network models to analyze urban mobility and system robustness.

Disaster type-based evaluation showed a significant focus on natural disasters; 15.8% of studies were on earthquakes, 11.2% on floods, and 13.2% on hurricanes, as in Wu and Chen (2023), Dong et al. (2023), Testa et al. (2015), and Chan and Schofer (2016). Disasters like tsunamis and landslides were less commonly studied and addressed in a few studies, such as Trucco et al. (2013) and Miele et al. (2021). A limited number of studies focused on environmental changes, particularly climate change, for which Schweikert et al. (2015) advocated for adaptive transportation infrastructures. 7.9% of the studies addressed man-made disruptions, such as cyber threats to maritime transportation systems, as studied by Drazovich et al. (2021). Other disasters cover a wide range of hypothetical and operational disruptions, accounting for 28.3% of the studies, with examples from Liu et al. (2021) and Twumasi-Boakye and Sobanjo (2021). Even multi-hazard cases were addressed by Chen et al. (2023), which contributes to the diversity of disaster conditions.

Table 2. Categorization of Transportation Resilience Studies by Systems

Category	Subcategory	Percentage of Studies	Specific Focus
		by Transportation System	
Road	Road Networks	**41.8%**	Motorways, highways, arterials, streets
	Road-Bridge Networks	**7.1%**	Road segments with integral bridge structures
Rail	Urban Rail Systems	**7.1%**	Subways, trams, urban rail
	Intercity and Freight Rail	**7.1%**	Long-distance passenger and freight rail services
Air	Networks & Operations	**5.0%**	Airport infrastructure and services management
Water	Networks & Operations	**5.0%**	Ports, shipping lanes, maritime logistics
Public	Mass Transit Systems	**5.0%**	Bus, shuttles, Light rail, metros, commuter trains
Multimodal	Integrated/ Intermodal	**10.6%**	Multiple transport modes
Specialized/Other	General Transport Focus	**11.3%**	Studies on general transportation systems
		by Disaster Type	
Natural Disasters	Earthquake	**15.8%**	Seismic events, soil liquefaction
	Flood	**11.2%**	Floods, Urban flooding
	Hurricane/Tropical Storm	**13.2%**	Hurricane Katrina, Hurricane Sandy, as such
	Tsunami	**2.6%**	Tsunami, seismic hazards
	Landslide	**2.0%**	Landslide incidents
Environmental & Climatic Changes	Severe Weather/Snowstorm	**2.6%**	Snowstorms, extreme weather events
	Climate Change	**3.9%**	Climate stressors, environmental impacts
Man-Made Disasters	Man-Made Disruptions	**7.9%**	Terrorism, violence, cybersecurity, etc.
Other	Multi-Hazard	**12.5%**	Combined hazards, diverse disaster scenarios
	Various/Miscellaneous	**28.3%**	Broad various disasters, simulated, hypothetical

The complex nature of resilience in transportation systems, examined through various dimensions and methodologies, reveals that there is no universally agreed-upon definition for resilience. The last task of the in-depth analysis involved exploring various definitions, metrics, models, indices, and measurement methods. Resilience definitions can be grouped into five major perspectives: (i) Functional & Operational Capacity, focusing on the continuity of service and operational aspects; (ii) Recovery & Adaptation Capability, emphasizing adaptive processes and recovery strategies; (iii) Network Level Measures, detailing empirical resilience metrics and analytical models; (iv) Context-Specific Measures, tailored to particular types of disruptions; and (v) Comprehensive and Integrated Nature which synthesize multiple resilience dimensions into a unified framework. The characteristic metrics, models, methodologies, and indices for each cluster are summarized, along with some example studies in Table 3. Although these clusters possess unique characteristics, they are interconnected in various aspects of transport systems resilience. The variety and connections among these clusters show a rich and complex landscape of resilience research in transportation systems. This variety of methods and measurements requires an integrated resilience framework –a synthesis of knowledge addressing the various dimensions of resilience. This necessity aligns with the objectives of this study, which are to simplify and define aspects of resilience in transportation systems, particularly in the context of natural disasters. By doing so, this study contributes to the critical discussion on disaster preparedness and recovery, providing a comprehensive resource for future resilience–focused work in transportation.

Table 3. Clusters of Resilience Definitions and Measurement Approaches in Transportation Literature

Cluster	Brief Summary	Some Key Metrics, Models, Indices and Methods	Example Studies
Functional & Operational Capacity	Maintaining or restoring system functionality & operational capacity after disruptions; assessing service levels & connectivity.	**Metrics:** Travel time, Service level (LOS, on-time arrival), Efficiency (speed, throughput), Network capacity, Safety **Models:** Traffic assignment models, System-based models **Indices:** Performance-based indices (combining travel time, efficiency, etc.), Resilience Triangle, Network connectivity indices **Methods:** Redundancy analysis, Scenario analysis	(Twumasi-Boakye and Sobanjo, 2018); (Vishnu et al., 2018); (Janić, 2018); (Nogal and O'Connor, 2018); (Murray-Tuite, 2006)
Recovery & Adaptation Capability	System's capacity to recover & adapt to post-disruption, including adaptive, absorptive, and restorative processes.	**Metrics:** Recovery/Restoration time, Repair costs, and delays, Flexibility, Capacity, Accessibility, Reliability **Models:** Agent-based models (ABMs), Traffic assignment models, Optimization models **Indices:** Rapid Recovery index, Recovery Ratio, Recovery Time, **Methods:** Vulnerability assessment, Fragility, and risk analysis	(Cimellaro et al., 2021); (Wang et al., 2021); (Twumasi-Boakye and Sobanjo, 2021); (Omer et al., 2012); (Zhang et al., 2009);
Network Level Measures	Empirical resilience metrics derived from mathematical models, simulations, network analysis, structural, and topological network properties.	**Metrics:** Network connectivity measures, Betweenness centrality, Closeness centrality, Graph theory indicators **Models:** Network-based models, System dynamics models. **Indices:** Indices for network structure (e.g., Global Efficiency) **Methods:** Network science techniques, Monte Carlo simulations	(Rouhana and Jawad, 2021); (Hu and Bhouri, 2020); (Kammouh et al., 2018); (Aydin et al., 2018); (Berche et al., 2009)
Context-Specific Measures	Resilience strategies specific to the type of disruption, i.e., natural disasters or technological failures, focus on customized measures.	**Metrics:** Evacuation time, Accessibility after disasters, System performance levels **Models:** Evacuation simulations, Accessibility models, Risk assessment models **Methods:** Scenario planning, post-disaster network evaluation,	(He et al., 2021); (Castro et al., 2018); (Liao et al., 2018); (Ye and Ukkusuri, 2015); (Davis et al., 2014);
Comprehensive & Integrated Nature	Combining multiple dimensions of resilience, integrating technical, organizational, social, and economic perspectives using systemic methodologies.	**Metrics & Indices:** Combines various metrics and indices from other clusters (e.g., Overall system functionality, Resilience Index) **Models:** Multi-criteria decision analysis, System-based models, Network models, Agent-based models **Methods:** Systemic risk assessment frameworks, Combining network analysis, Vulnerability assessment, Cost-Benefit analysis	(Anderson et al., 2022); (Koc et al., 2020); (Santos et al., 2020); (Machado-León and Goodchild, 2017) (Serulle et al., 2011)

4. Discussion

There has been an increasing interest and academic focus on resilience in transportation systems, picking up speed after global initiatives like the Hyogo Framework for Action in 2005. Bibliometric analysis showed that vulnerability and robustness are two major concepts in most studies. While the "climate change" keyword was commonly used in abstract-based search datasets, it was less prominent in title-based searches. The in-depth analysis revealed five primary clusters of definition perspectives on transportation system resilience, varying from ensuring operational integrity to achieving long-term adaptability. The literature mostly focused on "Functional & Operational" aspects and "Recovery & Adaptation". Network Level Measure studies employed quantitative methods (e.g., Monte Carlo simulations, mathematical models), highlighting the importance of maintaining network operations during crises and the need for systems to adapt and recover over time. While analysis revealed a significant focus on road transportation, other modes, such as maritime and rail transport, remain underrepresented and require further investigation.

5. Conclusions

The comprehensive overview of the literature on transportation system resilience showed a fragmented nature across different disaster types and transportation modes. While earthquakes, floods, and hurricanes were studied extensively, landslides, tsunamis, etc., were addressed less. Road transportation resilience attracts more interest due to the vulnerability of critical elements (e.g., bridges and tunnels) and their significant role in disaster management. However, findings also revealed that resilience is not a uniformly defined concept, reflecting the complex requirements of various disaster scenarios and transportation modalities. This diversity highlights the necessity for an integrated approach to resilience that addresses the complexities of disaster-type-based preparedness and recovery. The scope of transport system resilience can be defined from five major perspectives: i) Functional & Operational Capacity, ii) Recovery & Adaptation Capability, iii) Network Level Measures, iv) Context-Specific Measures, and v) Comprehensive & Integrated Nature.

Climate change is a major cause of the increasing frequency and severity of disasters, triggering many resilience studies. Due to the escalating risk of natural disasters from climate change, improving transportation systems resilience is increasingly crucial. Most transportation resilience studies mention climate change at a motivational level and focus on specific aspects, resulting in a complex and diverse landscape in disaster management. In addition to climate change, transportation system resilience during earthquakes is another major research area. However, resilience in transportation systems should be addressed within a unified framework that consolidates various definitions and measurements, regardless of the underlying disaster mechanisms. Future research and analyses should consider underrepresented modes (e.g., maritime and rail) and emerging challenges with a multi-scale (city, intercity, national) and multi-hazard (floods, hurricanes) scope. This framework should evaluate the vulnerabilities of different transportation systems to estimate total resilience in the region effectively.

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