

Rethinking the Vision of Transportation Resilience: A Five-Dimensional Framework

Abdullah Ugur Topal¹[0000-0002-0505-6551], Hande Demirel²[0000-0003-0338-791X], and Arif Cagdas Aydinoglu³[0000-0003-4912-9027]

¹ Transportation Technologies Institute, Gebze Technical University, 41400 Kocaeli, Türkiye
autopal@gtu.edu.tr

² Department of Geomatics Engineering, Civil Engineering Faculty,
Istanbul Technical University, 34469 Istanbul, Türkiye
hande.demirel@itu.edu.tr

³ Department of Geomatics Engineering, Gebze Technical University, 41400 Kocaeli, Türkiye
aydinoglu@gtu.edu.tr

Keywords: Transportation, Resilience, Vulnerability, Vision of Transportation Resilience, Future of Transportation.

Abstract

Transportation systems play a critical role in supporting economic and social sustainability, yet they are exposed to a range of vulnerabilities, including natural disasters, climate change, infrastructure failures, and human-induced disruptions. In this context, assessing the resilience and service continuity of transportation systems has emerged as a key research area. This research explores critical issues in transportation resilience, highlighting existing limitations and areas for improvement. While previous studies have addressed certain aspects of resilience (e.g., only topological indicators, single-mode network behavior, or static network structure), they often fall short of meeting the complex demands of contemporary urban transportation systems, indicating a clear need for new perspectives and approaches. To operationalize the proposed framework, a stepwise algorithm is developed that integrates heterogeneous data, monitors system dynamics, measures resilience metrics, predicts disruptions, and implements adaptive interventions. To further illustrate its applicability, the framework is demonstrated through two representative campus-scale scenarios addressing flood resilience management and air quality-driven mobility guidance. By conceptualizing transportation resilience through five key dimensions—integrate, observe, measure, predict and adapt,—this research proposes a comprehensive framework intended to advance both theoretical understanding and practical implementation in urban planning contexts.

1. Introduction

Resilience refers to a system's ability to withstand disruptions, mitigate their effects, and maintain an acceptable level of service. It also includes the capacity to recover and return to normal operation within a reasonable timeframe and cost (Gonçalves and Ribeiro, 2020). Transportation systems play a critical role in supporting economic activity and social well-being, yet they are highly vulnerable to natural disasters, infrastructure failures, climate-related events, and other unexpected disruptions. For example, in 2022, natural disasters worldwide caused estimated economic losses of approximately USD 313 billion (AON, 2023). The 2021 floods in Western Germany and Eastern Belgium resulted in over 130 fatalities in the Ahr Valley and 38 deaths in Belgium's Vesdre Valley, while around 6,500 homes and businesses in Luxembourg were affected, with total damages estimated at USD 46 billion (BBC, 2021; Yorke, 2023). More recently, flash floods in Valencia, Spain, led to over 220 fatalities and damage to approximately 100,000 vehicles, with economic losses expected to reach billions of dollars (Beake, 2024). Such events underscore the direct and critical impact of natural disasters on transportation networks and urban infrastructure.

While existing studies have explored certain aspects of transportation resilience, they often fall short due to their focus on single modes, static scenarios, or the limited applicability of existing resilience metrics. This highlights the need for forward-looking perspectives that consider multimodal integration, dynamic modeling, and emerging mobility trends. In this context, the present study aims to provide a novel framework for enhancing urban transportation resilience, offering both

theoretical insights and practical guidance for planning and management.

2. Literature Review

Transportation resilience has become an increasingly important research area due to the growing complexity and interconnectivity of modern transport systems. Although numerous studies have investigated resilience approaches, critical gaps remain, particularly with respect to the transition from single-mode to multimodal transportation, the development of new resilience metrics, and the implementation of real-time management strategies. These gaps can be organized into three key research challenges, each of which is addressed in the following subsections.

2.1 Measuring Resilience in Transportation System

Resilience analysis of transportation systems in the literature generally follows two main approaches. The first is graph-based theory, focusing on the topological properties of transportation networks and identifying structurally weak nodes and links through indicators such as betweenness centrality, node degree, and clustering coefficient. While these measures are computationally efficient and effective for large-scale networks, they do not capture actual traffic dynamics or redistribution effects under disruptions. The second approach is performance-based, considering dynamic aspects such as demand, capacity, and travel time to evaluate how service levels change before, during, and after disruptive events. Unlike purely topological

measures, this approach provides a more realistic assessment of resilience by reflecting user impacts and recovery processes (Serdar et al., 2021; Mattsson and Jenelius, 2015).

Several studies have applied both graph-based theory and performance-based approaches to assess the vulnerability and resilience of transportation systems. For example, in Northern Sweden, road networks were analyzed by testing the effects of random versus critical link closures, highlighting the importance of heavily used roads (Jenelius et al., 2006). Other research has evaluated efficiency, connectivity, and compactness metrics to identify the most influential links contributing to network vulnerability (Zhang et al., 2015). In the context of natural hazards, the Turkish air transport network was assessed under potential disruption scenarios using centrality measures such as betweenness, straightness, and closeness (Hamamci et al., 2017). Performance-based approaches have also been explored, such as evaluating recovery time and capacity changes of transport infrastructure following floods (Mojtahedi et al., 2016) or employing optimization and dynamic traffic simulation models to analyze resilience in real urban networks (Liao et al., 2018).

Research gap 1: Many studies in literature examine transportation systems solely from a topological perspective or evaluate them under performance-based conditions. However, these unidirectional approaches are insufficient for a comprehensive analysis of network resilience. Effective resilience assessment requires the integration of both static (structural) and dynamic (time-varying performance) approaches (Henry et al., 2021). In addition, there is a need to identify and develop new metrics that more effectively capture the resilience characteristics of transportation systems (Gonçalves and Ribeiro, 2020).

2.2 Transition Multimodal Transportation Resilience

Much of the existing literature addresses transportation networks through single-mode perspectives (e.g., road or rail), resulting in analyses that do not fully capture intermodal interactions. While road transport has been the focus of some studies (Lin et al., 2024), the importance of integrating other modes, such as public transit, for future multimodal analyses has also been emphasized.

Transportation networks are typically interconnected and interdependent, meaning disruptions in one mode can trigger cascading failures across the system. Conversely, in some cases, one mode may compensate for disruptions in another (Zhou et al., 2019). Therefore, considering interactions among different modes is essential for comprehensive multimodal network analysis. Finally, the potential of alternative mobility options, such as micro-mobility modes (e.g., e-scooters) (Rebally et al., 2021), to enhance system flexibility during disruptive events has received insufficient attention. These modes, however, can play a crucial role in providing last mile connectivity (Serdar et al., 2021).

Research gap 2: Although existing studies have addressed resilience within individual transport modes, only a few have examined the integrated behavior of multimodal systems during disruptions, and even fewer have incorporated micro-mobility modes into resilience analyses. There is a need for novel approaches to model multimodal urban transportation networks by integrating components such as road infrastructure, metro stations, and bicycle networks into a unified graph-based framework.

2.3 Real Time Management Transport Resilience

In terms of transportation system resilience, the integration of real-time data and the use of sensor measurements are crucial for modeling traffic flows and demand fluctuations with greater precision and realism (Lin et al., 2024; Bergantino et al., 2024). However, most existing traffic models are based on the assumption of fixed travel demand. For instance, the User Equilibrium model is developed under a constant demand assumption. In contrast, during extraordinary events such as disasters, travel behavior may change significantly, and some trips may be canceled. Therefore, the development and application of elastic-demand models that account for variations in travel demand are essential (Lin and Lin, 2022). In this context, establishing digital twin infrastructures and integrating sensor technologies are critical for real-time and accurate monitoring of transportation systems. Such capabilities enable realistic resilience analyses and allow demand fluctuations during crises to be managed and mitigated through timely interventions. Similarly, dynamic flood models are needed, as static approaches fail to reflect the real-time impacts of disruptions on transport networks (Pyatkova et al., 2019). To improve realism, resilience analyses should incorporate holistic simulations that capture diverse infrastructures and their interdependencies (Dong et al., 2022).

Research gap 3: Most existing studies are limited to static data and have been tested only on region-specific scenarios. In contrast, research that leverages real-time data integration to enable the immediate management of disasters remains very limited.

Overarching research gap: While previous studies have addressed certain aspects of transportation resilience, they often focus on isolated dimensions or static analyses, highlighting the need for a comprehensive framework that captures the interdependencies, adaptability, and dynamic behavior of urban mobility systems.

To address these gaps, this study proposes a comprehensive resilience framework structured around five dimensions—integrate, observe, measure, predict, and adapt. Its applicability is demonstrated through two campus-scale scenarios: one addressing flood resilience and another guiding users for improved air quality and sustainable mobility.

3. Methodology

Traditional approaches to transportation resilience often focus on a single aspect of the system, such as infrastructure robustness or recovery time, thereby providing only a partial representation of system behavior under stress. Such approaches tend to overlook the complex interdependencies among network components, modes, and users, as well as the dynamic and time-varying nature of urban mobility systems. As a result, they are limited in their ability to adequately capture cascading failures, adaptive responses, and long-term system performance under both normal and disrupted conditions.

3.1 The Proposed Five-Dimensional Framework

To address these limitations, there is a clear need for a holistic and integrative framework capable of representing transportation systems as complex, adaptive entities. Such a framework should combine static and dynamic perspectives, be supported by real-time data, and consider all transportation modes to enable the development of next-generation resilience metrics. In this study,

a comprehensive framework is proposed to better reflect the complexity, resilience, and adaptability of contemporary urban transportation systems. The framework is structured around five interrelated dimensions—Integrate, Observe, Measure, Predict, and Adapt (see Figure 1)—which together provide a systematic basis for assessing system resilience and supporting informed decision-making in urban transportation planning and management.

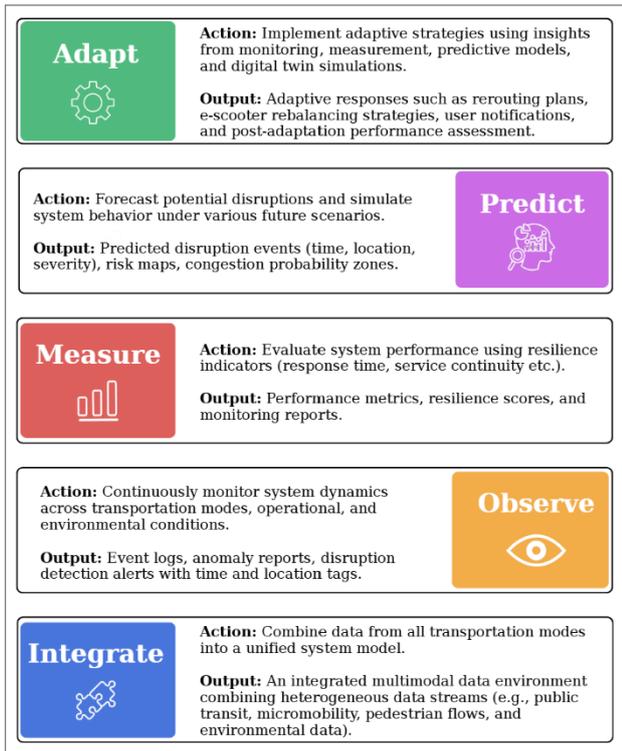


Figure 1. Operational structure of the proposed transportation resilience framework.

These dimensions were selected to collectively address the critical facets of transportation resilience, ensuring that no single aspect dominates the analysis while maintaining clarity and practical applicability. Each dimension contributes a distinct perspective: integration ensures system-wide coordination, adaptation supports flexibility, observation enables real-time awareness, measurement provides quantitative evaluation, and prediction allows for proactive planning. Together, they form a complementary and interconnected framework for resilience analysis. The following sections provide a detailed explanation of each dimension, outlining its rationale, scope, and role within the overall framework.

Integrate: Contemporary cities are increasingly characterized by multimodal transportation environments, where the integration of transportation modes, data sources, and system components is essential. Future research should focus on approaches that integrate transportation modes, heterogeneous data, and systems while explicitly accounting for their interdependence. Such integration is critical for enabling comprehensive assessments of system-wide performance and for providing decision-makers with actionable insights to support holistic planning and adaptive management strategies.

Observe: Current resilience analyses often rely on static models that fail to capture real-time system behavior under rapidly changing conditions, such as natural disasters or emergencies.

There is a pressing need for approaches that integrate real-time data and dynamic modeling to monitor system vulnerabilities, evaluate demand fluctuations, and support timely interventions.

Measure: Conventional performance metrics may not fully capture the adaptive capacity and complex behavior of urban transportation systems during disruptions. Future research should develop advanced resilience metrics that consider recovery time, network redundancy, and intermodal dependencies, providing a more accurate quantification of system performance and informing robust planning decisions.

Predict: The growing availability of spatial and data-driven sources—such as smart card data, sensor measurements, and mobile application data—offers significant potential for predictive modeling. Integrating these data into simulation frameworks can enable anticipation of travel demand fluctuations, forecasting of traffic patterns, and evaluation of potential impacts from disruptive events, supporting proactive resilience strategies.

Adapt: Emerging transportation modes, such as micro-mobility and alternative transport options, present significant opportunities to enhance urban mobility resilience, particularly in last mile scenarios. Future studies should investigate how these modes can be effectively incorporated into resilience frameworks to improve system adaptability and flexibility.

3.2 Mathematical Formulation

We define the system performance at time t as $P(t)$. The resilience of the system over a disruption period $[t_0, t_n]$ can be quantified as:

$$R_{\{Total\}} = \int_{\{t_0\}}^{\{t_n\}} P(t) dt \quad (1)$$

The five dimensions act as operators on the performance function $P(t)$:

1. **Integrate (I) & Observe (O):** These dimensions determine the detection latency (t_d). A high efficiency in I and O minimizes the time between the event and the response.

2. **Measure (M):** Quantifies the instantaneous loss

$$L(t) = P_{\{nominal\}(t)} - P_{\{actual\}(t)} \quad (2)$$

3. **Predict (P):** A feed-forward operator that estimates the future state

$$P(t + \Delta t) \quad (3)$$

allowing for pre-emptive mitigation.

4. **Adapt (A):** A feedback controller that adjusts system parameters (e.g., signal timings, rerouting) to maximize the recovery rate

$$\rho = \frac{dP}{dt} \quad (4)$$

3.3 The Proposed Algorithm

The following pseudo-code describes the interaction between the five dimensions in a real-world transportation management scenario:

Algorithm 1

Input:

- Multi-source Data Sets: \mathcal{D}
- Nominal Performance: P_{nominal}
- Action Set: $\mathcal{A} = \{a_1, a_2, \dots, a_n\}$
- Resilience Threshold: τ

Output:

- Optimal Adaptation Action: a^*
- Recovery Rate: ρ

1. **Initialize:** $a^* \leftarrow \emptyset, \rho_{\text{max}} \leftarrow 0$
2. **While** system is active **do**
3. **Step 1: INTEGRATE – Data Fusion**
4. $S_{\text{current}} \leftarrow \text{DataFusion}(\mathcal{D})$
5. **Step 2: OBSERVE – Monitoring**
6. $P_{\text{actual}}(t) \leftarrow \text{CalculatePerformance}(S_{\text{current}})$
7. **If** $P_{\text{actual}}(t) < \tau$ **then**
8. **Step 3: MEASURE – Loss Quantification**
9. $L(t) \leftarrow P_{\text{nominal}}(t) - P_{\text{actual}}(t)$
10. **Step 4: PREDICT – Future State Simulation**
11. $S_{\text{future}} \leftarrow \text{PredictPropagation}(S_{\text{current}}, L(t))$
12. **Step 5: ADAPT – Optimization Loop**
13. **For all** $a_i \in \mathcal{A}$ **do**
14. $S_{\text{sim}} \leftarrow \text{SimulateIntervention}(S_{\text{future}}, a_i)$
15. $\rho_i \leftarrow \frac{dP}{dt}(S_{\text{sim}})$
16. **If** $\rho_i > \rho_{\text{max}}$ **then**
17. $a^* \leftarrow a_i$
18. $\rho_{\text{max}} \leftarrow \rho_i$
19. **End If**
20. **End For**
21. Execute(a^*)
22. **End If**
23. **End While**

4. Illustrative Future Perspective

To demonstrate how the proposed five-dimensional framework can be applied in practice and guide future resilience strategies, this section presents an illustrative perspective. Rather than offering a definitive application, the aim is to show how the dimensions of Integrate, Observe, Measure, Predict and Adapt may interact within a realistic context. By envisioning a campus-scale digital twin environment, the framework can be explored through multimodal integration, adaptive mobility solutions, real-time monitoring, advanced metrics, and predictive scenario modeling (see Figure 2). This illustrative perspective highlights the potential of the framework to inform both future research and practical planning efforts.

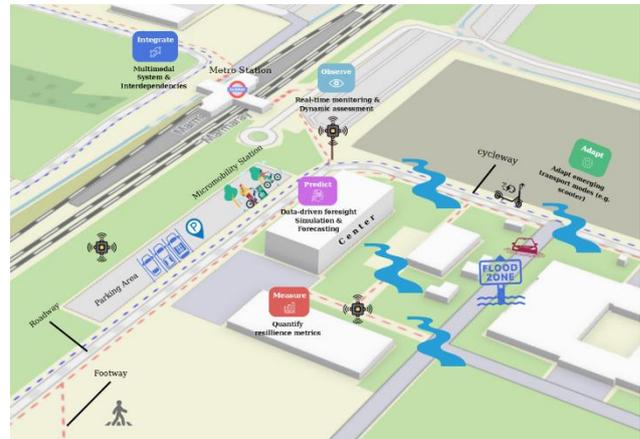


Figure 2. Illustration of the proposed five-dimensional framework applied in a campus-scale digital twin environment.

To operationalize the proposed five-dimensional framework, a sequential process can be established to enhance transportation resilience within a multimodal system, such as a university campus. First, **integration** involves consolidating real-time data from various sources, including IoT sensors, camera, GNSS receiver, and environmental monitors, to build a unified digital twin model of the transportation network that encompasses shuttles, e-scooters, bike lanes, and pedestrian pathways. Next, the **observation** phase continuously monitors system performance by detecting anomalies like vehicle delays, route blockages, or changes in user demand. Following this, the **measurement** step evaluates key resilience indicators—such as response time, service continuity, and delay propagation—to provide quantitative assessments of system robustness in real time. The **prediction** stage leverages machine learning and simulation techniques to forecast potential disruptions, anticipate congestion hotspots, and model the impacts of environmental factors. Finally, the **adaptation** phase implements responsive strategies, including dynamic rerouting, resource reallocation, and real-time user notifications, to mitigate the effects of disruptions and restore service continuity.

The practical utility of the proposed framework can be highlighted through two illustrative campus-scale scenarios.

The first scenario focuses on flood resilience within a campus-scale multimodal system. During extreme rainfall, several road segments become inundated, restricting shuttle circulation and disrupting pedestrian pathways. Through **Integration**, real-time data from rainfall sensors, CCTV cameras, and mobility services feed into the digital twin model. **Observation** detects abnormal conditions, such as rising water levels or sudden route blockages. **Measurement** quantifies the extent of disruption by calculating the percentage of road closures, affected nodes, and increased travel times across the network. **Prediction** models the likely spread of flooding and anticipates secondary impacts, such as congestion on alternative routes. Finally, **Adaptation** provides dynamic rerouting for shuttles, promotes micro-mobility use on unaffected pathways, and issues timely alerts to users. This scenario illustrates how the framework can guide proactive and coordinated responses to natural hazards, thereby enhancing the resilience of transportation systems.

A second scenario focuses on long-term environmental stress, specifically declining air quality and elevated carbon emissions. During periods of high PM2.5 and CO₂ concentrations, outdoor pathways and cycling routes become less accessible, and commuter health is at risk. **Integration** collects data from air

quality and emission sensors, traffic flow, and mobility applications into the digital twin. **Observation** pinpoints pollution hotspots and areas with high traffic-induced emissions. **Measurement** evaluates the system's resilience by applying metrics that capture both mobility and environmental dimensions, including the proportion of low-emission routes utilized, reduction in exposure to polluted areas, and adaptive capacity of the network to maintain user access under degraded conditions. **Prediction** forecasts the spread of pollutants and anticipates user behavior changes, such as increased adoption of low-emission travel options. Through **Adaptation**, users are guided along "green" corridors with better air quality, shuttle services are adjusted to reduce emissions, and app-based incentives encourage the use of sustainable travel modes. This scenario demonstrates how the framework can support not only operational adjustments but also user-centered strategies that promote healthier, low-carbon, and environmentally responsible travel.

5. Conclusion

This study underscores the critical importance of resilience in contemporary transportation systems, which are increasingly exposed to natural disasters, extreme weather events, climate change impacts, infrastructure failures, and human-induced disruptions. By proposing a five-dimensional framework—Integrate, Observe, Measure, Predict, and Adapt—the research provides a holistic, adaptive, and systematic perspective on resilience that links both technical infrastructure considerations and broader systemic dynamics, including multimodal interactions and user behavior.

A key contribution of this work lies in addressing gaps in the current literature, where comprehensive, systems-level, and multimodal approaches remain limited. The framework demonstrates the potential to quantify resilience using advanced metrics that integrate structural, operational, and environmental dimensions, while also highlighting the value of real-time monitoring, predictive modeling, and adaptive interventions. These capabilities are illustrated through two representative campus-scale scenarios.

In the first scenario, resilience management during flood events is supported by real-time environmental sensing and predictive flood modeling, enabling adaptive campus operations such as dynamic access control, safe route allocation, and the prioritization of critical facilities. This scenario demonstrates how integrated data-driven interventions can reduce disruption, enhance safety, and improve overall system robustness during extreme events.

In the second scenario, the framework focuses on air quality management by continuously monitoring environmental conditions and actively guiding campus users toward green corridors and low-exposure pathways. By combining real-time air quality data with user-centered routing strategies and incentive mechanisms, the system not only improves individual exposure outcomes but also encourages sustainable mobility patterns, contributing to reduced emissions and enhanced environmental resilience.

From a practical perspective, the framework offers actionable guidance for urban planners, infrastructure managers, and policymakers. It enables proactive decision-making under diverse stress scenarios, supports multimodal transport integration, leverages digital twins for scenario testing, and encourages the adoption of emerging mobility solutions. By

bridging theory and practice, it lays a foundation for more resilient, adaptive, and sustainable urban transportation networks.

Future studies may focus on extending the framework to real-world settings by incorporating large-scale implementations, long-term monitoring of transportation networks, and closer integration with advanced simulation techniques and machine learning methods to further improve resilience assessment. In addition, examining policy dimensions, long-term environmental outcomes, and the behavioral responses of commuters could provide valuable insights into the broader impacts of such systems. Overall, strengthening urban transportation resilience should be viewed as a continuous and evolving effort, requiring ongoing assessment, coordination across multiple transport modes, adaptable operational practices, and the alignment of resilience planning with sustainability goals to ensure that mobility systems can effectively respond to the complex demands of contemporary urban environments.

Acknowledgements

This work was supported by the project ADEP:2024-A-113-09 in Türkiye, "Development of Smart City Applications for Climate Change Using Artificial Intelligence Techniques in Digital Twin Spatial Data Infrastructures."

References

- AON, 2023. Weather, Climate and Catastrophe Insight. <https://aon.com/getmedia/f34ec133-3175-406c-9e0b-25cea768c5cf/20230125-weather-climate-catastrophe-insight.pdf> (20 August 2025).
- BBC, 2021. Avrupa'daki sel felaketi: Almanya'daki trajediden alınan dersler. <https://www.bbc.com/turkce/haberler-dunya-59088472> (20 August 2025).
- Beake, N., 2024. Valencia floods: Spain clings to fragments of hope in time of disaster. *BBC*. <https://www.bbc.com/news/articles/c3v111511gvo> (20 August 2025).
- Bergantino, A.S., Gardelli, A., Rotaris, L., 2024. Assessing transport network resilience: empirical insights from real-world data studies. *Transport Reviews*, 44, 834–857. doi.org/10.1080/01441647.2024.2322434.
- Dong, B.-X., Shan, M., Hwang, B.-G., 2022. Simulation of transportation infrastructures resilience: A comprehensive review. *Environmental Science and Pollution Research*, 29(9), 12965–12983. doi.org/10.1007/s11356-021-18033-w.
- Gonçalves, L.A.P.J., Ribeiro, P.J.G., 2020. Resilience of urban transportation systems. Concept, characteristics, and methods. *Journal of Transport Geography*, 85, 102727. doi.org/10.1016/j.jtrangeo.2020.102727.
- Hamamci, S.F., Ozdemir, E., Demirel, H., 2019. Vulnerability analysis for air transportation network: A natural disaster scenario for Turkey. *Fresenius Environmental Bulletin*. doi.org/10.81043/aperta.100103.
- Henry, E., Furno, A., Faouzi, N.-E.E., 2021. REINFORCE: rapid augmentation of large-scale multi-modal transport networks for resilience enhancement. *Applied Network Science*, 6. doi.org/10.1007/s41109-021-00422-2.

Jenelius, E., Petersen, T., Mattsson, L.-G., 2006. Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice*, 40, 537–560. doi.org/10.1016/j.tra.2005.11.003.

Liao, T.-Y., Hu, T.-Y., Ko, Y.-N., 2018. A resilience optimization model for transportation networks under disasters. *Natural Hazards*, 93, 469–489. doi.org/10.1007/s11069-018-3310-3.

Lin, J., Lin, W., 2022. Transportation System Vulnerability Assessment considering Environmental Impact. *Journal of Advanced Transportation*, 2022, 1–12. doi.org/10.1155/2022/8711894.

Lin, X., Lu, Q., Chen, L., Brilakis, I., 2024. Assessing dynamic congestion risks of flood-disrupted transportation network systems through time-variant topological analysis and traffic demand dynamics. *Advanced Engineering Informatics*, 62, 102672. doi.org/10.1016/j.aei.2024.102672.

Mattsson, L.-G., Jenelius, E., 2015. Vulnerability and resilience of transport systems – A discussion of recent research. *Transportation Research Part A: Policy and Practice*, 81, 16–34. doi.org/10.1016/j.tra.2015.06.002.

Mojtahedi, M., Newton, S., Von Meding, J., 2016. Predicting the resilience of transport infrastructure to a natural disaster using Cox's proportional hazards regression model. *Natural Hazards*, 85, 1119–1133. doi.org/10.1007/s11069-016-2624-2.

Pyatkova, K., Chen, A.S., Butler, D., Vojinović, Z., Djordjević, S., 2019. Assessing the knock-on effects of flooding on road transportation. *Journal of Environmental Management*, 244, 48–60. doi.org/10.1016/j.jenvman.2019.05.013.

Rebally, A., Valeo, C., He, J., Saidi, S., 2021. Flood impact assessments on transportation networks: A review of methods and associated temporal and spatial scales. *Frontiers in Sustainable Cities*, 3, 732181. doi.org/10.3389/frsc.2021.732181.

Serdar, M.Z., Koç, M., Al-Ghamdi, S.G., 2021. Urban Transportation Networks Resilience: Indicators, disturbances, and assessment methods. *Sustainable Cities and Society*, 76, 103452. doi.org/10.1016/j.scs.2021.103452.

Yorke, O., 2023. Unforgettable: The Devastating European Floods of 2021. *Climate X*. <https://www.climate-x.com/articles/industry/unforgettable-the-devastating-european-floods-of-2021> (20 August 2025).

Zhang, X., Miller-Hooks, E., Denny, K., 2015. Assessing the role of network topology in transportation network resilience. *Journal of Transport Geography*, 46, 35–45. doi.org/10.1016/j.jtrangeo.2015.05.006.

Zhou, Y., Wang, J., Yang, H., 2019. Resilience of Transportation Systems: Concepts and Comprehensive review. *IEEE Transactions on Intelligent Transportation Systems*, 20, 4262–4276. doi.org/10.1109/tits.2018.2883766.