

Smart resilient transportation architectures as enablers of supply chain continuity

Smart and
Resilient
Transportation

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Abstract

Purpose – Transportation systems are increasingly exposed to climate-related, operational and cyber disruptions that threaten the continuity of supply chains. Although smart transportation technologies enhance efficiency and visibility, they do not inherently ensure resilience. This study aims to develop and refine a smart resilient transportation architecture that explains how artificial intelligence (AI) and adaptive capacity can be systematically integrated to enable supply chain continuity under disruption conditions.

Design/methodology/approach – This study adopts a conceptual and systems-based design approach grounded in smart transportation systems and transportation resilience research. A multilayer architecture is developed that integrates sensing and data acquisition, AI-driven intelligence, adaptive control mechanisms and resilience capabilities.

Findings – This study shows that resilience emerges from architectural integration rather than isolated smart technologies. AI-enabled prediction and learning enhance adaptive capacity only when embedded within coordinated control mechanisms such as dynamic routing, intermodal switching and resource reallocation. The interaction of sensing, intelligence and adaptive control strengthens absorptive, adaptive and recovery capacities of transportation systems, thereby stabilizing physical flows and enabling supply chain continuity in the presence of disruptions.

Originality/value – This study develops a smart resilient transportation architecture that integrates sensing, AI-enabled intelligence, adaptive control, governance and resilience capabilities within a unified framework. The architecture explains how transportation systems can anticipate, respond to and recover from disruptions while maintaining logistics flows. By linking transportation resilience to supply chain continuity, this study provides a transportation-centric perspective that extends existing smart transportation and resilience research.

Keywords Smart transportation systems, Transportation resilience, Artificial intelligence, Adaptive capacity, Supply chain continuity, Intelligent transportation systems

Paper type Conceptual paper

1. Introduction

Transportation systems constitute the physical backbone of modern economies and supply chains, enabling the movement of goods across regions, markets and production networks (Amekudzi-Kennedy *et al.*, 2024). Their performance directly affects delivery reliability, lead time stability and the continuity of logistics flows. However, transportation networks are increasingly exposed to a wide range of disruptions, including extreme weather events, infrastructure degradation, traffic incidents, cyber threats and systemic shocks such as pandemics. These disruptions have repeatedly demonstrated that transportation failures often



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act as primary triggers of cascading supply chain breakdowns, rather than merely as secondary operational inconveniences (Craighead *et al.*, 2007; Ivanov and Dolgui, 2021).

In response to growing operational complexity and congestion, the concept of smart transportation systems has gained prominence. Intelligent transportation systems (ITS) integrate sensing technologies, communication networks and computational intelligence to improve traffic management, infrastructure monitoring and operational efficiency (Zhao, 2024). Prior research shows that real-time data, connectivity and automation can significantly enhance situational awareness and system performance under normal operating conditions (Afriyie *et al.*, 2019; Kaber and Endsley, 2004). More recently, advances in artificial intelligence (AI) and machine learning have further expanded the capabilities of smart transportation systems by enabling predictive analytics, anomaly detection and data-driven decision support (Nasiri *et al.*, 2020; Zemmouchi-Ghomari, 2025).

Despite these advances, smart transportation systems are not inherently resilient (Du *et al.*, 2022). Many digitalized transportation networks remain optimized for efficiency rather than robustness, leaving them vulnerable to disruptions that exceed expected operating conditions (Long *et al.*, 2020). Transportation resilience refers to the ability of a system to absorb disturbances, adapt to changing conditions and recover functionality within an acceptable time frame (Cheng and Yang, 2017; Esangbedo *et al.*, 2024). While resilience has become a central concept in infrastructure planning and risk management, it is often treated as an add-on to existing systems rather than as a fundamental design principle embedded within transportation architectures (Babaei *et al.*, 2025).

This separation between smartness and resilience represents a critical limitation in current research. Studies on smart transportation tend to focus on optimization, automation and efficiency gains, whereas resilience research emphasizes vulnerability assessment, redundancy and recovery planning (El Baz and Ruel, 2024). What remains insufficiently explored is how smart technologies particularly AI can be architecturally integrated to enable adaptive capacity, which is widely recognized as the core mechanism of resilience in complex systems (Ponomarov and Holcomb, 2009). Without such integration, digital intelligence may enhance visibility without translating into effective adaptive or recovery actions (Nurhayati *et al.*, 2022; Esangbedo *et al.*, 2024).

The implications of this gap are especially significant for supply chains. Although supply chain resilience has received substantial scholarly attention, transportation is frequently treated as one of several functional components alongside sourcing, inventory and production (Slater *et al.*, 2006). This perspective underestimates the structural role of transportation systems in governing physical flows. Empirical evidence suggests that transportation disruptions often propagate rapidly across supply chains, amplifying delays and uncertainty regardless of firm-level resilience strategies (Ivanov and Dolgui, 2020). Consequently, supply chain continuity is fundamentally contingent on the resilience of transportation systems (Xie *et al.*, 2020).

From a systems perspective, transportation should therefore be conceptualized not merely as a service input to supply chains but as a foundational enabler of continuity. Maintaining supply chain flows under disruption depends on transportation systems' ability to sense emerging threats, interpret evolving conditions, adapt operational decisions and recover network functionality. These capabilities cannot be achieved through isolated technologies or contingency plans alone; they require coherent system architectures that integrate intelligence, control and governance across transportation networks.

This study addresses this gap by developing a smart resilient transportation architecture that systematically integrates AI and adaptive capacity to enable supply chain continuity. Rather than viewing smart technologies and resilience strategies as separate domains, the

proposed architecture conceptualizes them as interdependent system layers whose interaction determines transportation performance under disruption. The framework emphasizes coordinated sensing, AI-driven intelligence, adaptive control mechanisms and emergent resilience capabilities, supported by governance structures that ensure interoperability and coordination. Importantly, supply chain continuity is positioned as a downstream outcome of transportation system performance, preserving a transportation-centric analytical focus.

This study contributes to the literature by developing an integrated architectural framework that links smart transportation technologies, AI-enabled adaptive capacity and transportation resilience (Amekudzi-Kennedy *et al.*, 2024). The framework explains how interactions among sensing, intelligence, adaptive control and governance mechanisms support transportation system performance under disruption conditions and ultimately enable supply chain continuity.

The remainder of the paper is structured as follows. Section 2 reviews the conceptual foundations of smart transportation systems, transportation resilience and adaptive capacity. Section 3 introduces the proposed smart resilient transportation architecture. Section 4 applies the architecture to disruption scenarios and identifies strategic pathways for supply chain continuity. Section 5 discusses managerial and policy implications, Section 6 outlines future research directions and boundary conditions and Section 7 concludes the study.

2. Conceptual foundations

2.1 Smart transportation systems

Smart transportation systems refer to the application of digital technologies, data analytics and intelligent control mechanisms to improve the efficiency, safety and performance of transportation networks (Tae-Seong, 2026). The concept is most operationalized through ITS, which integrate sensing technologies, communication infrastructure and computational intelligence to support real-time monitoring and decision-making (Afriyie *et al.*, 2019; Kaber and Endsley, 2004). Core components of smart transportation systems include traffic sensors, connected vehicles, vehicle to infrastructure communication and centralized or distributed traffic management platforms (Amekudzi-Kennedy *et al.*, 2024).

Recent advances in AI and machine learning have significantly expanded the scope of smart transportation. Data-driven models enable traffic flow prediction, incident detection, demand forecasting and adaptive signal control, allowing transportation systems to respond dynamically to changing conditions (Nasiri *et al.*, 2020; Zemmouchi-Ghomari, 2025). These capabilities have been shown to improve operational efficiency, reduce congestion and enhance situational awareness across transportation networks (Picone *et al.*, 2015).

However, the dominant focus of smart transportation research remains performance optimization under normal operating conditions (Haghighat *et al.*, 2020). Many ITS applications are designed to minimize travel time, maximize throughput or improve asset utilization, often assuming stable system conditions (Meneguet *et al.*, 2018). As a result, smart transportation systems may exhibit high efficiency but limited robustness when exposed to extreme or unexpected disruptions. This limitation highlights the need to complement smartness with resilience-oriented design principles.

2.2 Transportation resilience and adaptive capacity

Transportation resilience is commonly defined as the ability of a transportation system to withstand disruptions, maintain essential functionality and recover within an acceptable time frame (Cheng and Yang, 2017; Esangbedo *et al.*, 2024). Unlike traditional risk management approaches that emphasize prevention and reliability (Chen *et al.*, 2017), resilience focuses

on system behavior across the full disruption lifecycle, including absorption, adaptation and recovery (Alam *et al.*, 2016).

The resilience literature frequently distinguishes among three core capacities: absorptive capacity, adaptive capacity and recovery capacity (Anderson *et al.*, 2020). Absorptive capacity reflects the system's ability to tolerate disturbances without major performance loss, often supported by redundancy and robustness. Adaptive capacity refers to the ability to adjust operations in response to evolving conditions, such as rerouting traffic or reallocating capacity. Recovery capacity captures the speed and effectiveness with which system functionality can be restored after disruption (El Baz and Ruel, 2024).

Among these dimensions, adaptive capacity has gained increasing attention as transportation systems face more frequent and uncertain disruptions. Static design measures alone are insufficient in complex, interconnected networks. Adaptive capacity enables transportation systems to modify control strategies in real time, coordinate across modes and learn from past disruptions. Importantly, adaptive capacity is not solely a function of physical infrastructure; it emerges from the interaction of infrastructure, digital intelligence and institutional arrangements (Ponomarov and Holcomb, 2009).

2.3 Artificial intelligence as an enabler of adaptive transportation systems

AI plays a central role in enabling adaptive capacity within smart transportation systems. By processing large volumes of heterogeneous data from sensors, vehicles and infrastructure, AI supports predictive, prescriptive and learning based decision-making (Nasiri *et al.*, 2020). Machine learning techniques such as neural networks, anomaly detection and reinforcement learning have been widely applied to traffic prediction, incident management and dynamic control problems (Kaber and Endsley, 2004; Zemmouchi-Ghomari, 2025).

From a resilience perspective, AI contributes to multiple stages of the disruption lifecycle. Predictive analytics enhance absorptive capacity by identifying early warning signals and anticipating system stress. Real-time learning and optimization support adaptive capacity by enabling dynamic routing, scheduling and mode switching as conditions evolve. Postdisruption learning enhances recovery capacity by improving future responses based on historical disruption data (Ivanov and Dolgui, 2021).

Nevertheless, AI alone does not guarantee resilience. Without appropriate system architecture, AI outputs may remain disconnected from operational control or constrained by organizational silos. Prior studies emphasize that the resilience benefits of digital technologies depend on how intelligence is embedded within decision-making structures and governance frameworks (Xie *et al.*, 2026). This insight underscores the importance of shifting attention from individual AI applications toward integrated transportation system architectures.

2.4 Transportation systems as enablers of supply chain continuity

Supply chain continuity refers to the ability of supply chains to maintain the flow of goods and services despite disruptions (Xie *et al.*, 2020). While supply chain resilience research has extensively examined sourcing strategies, inventory buffers and network flexibility, transportation is often treated as one functional component among many (Slater *et al.*, 2006; Aslam *et al.*, 2025). This perspective underestimates the structural role of transportation systems in governing physical flows.

Empirical and simulation-based studies demonstrate that transportation disruptions frequently act as primary propagation mechanisms for supply chain failures, amplifying delays and uncertainty across interconnected networks (Craighead *et al.*, 2007; Ivanov and Dolgui, 2020).

When transportation systems lack adaptive and recovery capabilities, firm-level resilience measures may be insufficient to maintain continuity.

From a systems perspective, transportation should therefore be conceptualized as a foundational enabler of supply chain continuity (Du *et al.*, 2022). Transportation systems that can sense disruptions, adapt operational decisions and recover network functionality stabilize logistics flows and reduce disruption propagation. Importantly, this does not require transportation systems to be optimized for firm-level supply chain objectives; rather, continuity emerges as an outcome of resilient transportation system performance.

2.5 Synthesis and architectural implications

The preceding discussion reveals a critical gap in existing research. Smart transportation systems provide intelligence and efficiency, while transportation resilience emphasizes adaptability and recovery (Amekudzi-Kennedy *et al.*, 2024). However, these domains are rarely integrated through a coherent architectural lens. As a result, smart technologies may enhance visibility without enabling resilience, and resilience strategies may lack the intelligence required for dynamic adaptation.

The existing literature has contributed significantly to the understanding of smart transportation systems, transportation resilience and digital technologies (Wang *et al.*, 2026; Amekudzi-Kennedy *et al.*, 2024). However, prior studies have generally examined these domains independently, focusing either on transportation efficiency, resilience assessment or specific technological applications (Tetteh *et al.*, 2025). Limited attention has been devoted to developing an integrated architectural perspective that systematically explains how AI, adaptive control mechanisms and resilience capabilities interact to support supply chain continuity. Table 1 summarizes representative studies and highlights the research gap addressed by the present study.

An architectural perspective offers a means to bridge this gap by explicitly linking sensing, AI-driven intelligence, adaptive control and resilience capabilities within a unified system design. This perspective forms the conceptual foundation for the smart resilient transportation architecture developed in the next section, which positions resilience as an emergent outcome of integrated system design and supply chain continuity as a downstream result of transportation system performance.

3. Smart resilient transportation architecture

This section presents a smart resilient transportation architecture that explains how AI and adaptive capacity can be structurally embedded within transportation systems to enable resilience and supply chain continuity (Ganin *et al.*, 2019). As illustrated in Figure 1, the architecture adopts a multilayer cyber physical systems perspective, emphasizing the integration of sensing, intelligence, control and governance rather than isolated technological solutions. The central premise is that resilience emerges from the orchestration of architectural layers that collectively support anticipation, adaptation and recovery under disruption conditions. Figure 1 illustrates the proposed smart resilient transportation architecture, highlighting the integration of sensing, AI-driven intelligence, adaptive control mechanisms and resilience capabilities that collectively enable supply chain continuity.

3.1 Architectural overview and design logic

The proposed architecture conceptualizes transportation systems as dynamic and adaptive networks exposed to diverse external disruptions, including extreme weather events, infrastructure failures, congestion and cyber threats (Szeto, 2014). Consistent with systems

Table 1. Summary of prior research and research gap

Study	Primary focus	Limitation	Contribution of current study
Wang et al. (2026)	Resilience in intelligent transportation systems	Focuses on resilience concepts without integrated architectural design	Develops a multilayer transportation architecture integrating resilience and AI
Ganin et al. (2019)	Resilience in integrated urban transportation systems	Emphasizes resilience assessment rather than adaptive intelligence mechanisms	Explains how AI enables adaptive and recovery capabilities
Zhao (2024)	Smart transportation technology innovation	Primarily addresses performance and sustainability outcomes	Positions resilience as a core design objective
Nguyen et al. (2021)	Blockchain-enabled freight transportation systems	Technology-specific focus with limited resilience integration	Provides a system-level resilience architecture applicable across technologies
Amekudzi-Kennedy et al. (2024)	Capability development for transportation resilience	Focuses on resilience capabilities without architectural integration	Connects sensing, intelligence, adaptive control, and resilience within one framework
Current study	Smart resilient transportation architecture	—	Integrates AI, adaptive capacity, governance and resilience to explain supply chain continuity

Source(s): Author’s synthesis based on prior literature

engineering perspectives, resilience is treated as an emergent property resulting from interactions among system components rather than as a standalone attribute ([Cheng and Yang, 2017](#); [Xie et al., 2026](#)). [Figure 1](#) illustrates four core layers, sensing and data, AI intelligence, adaptive control and resilience capabilities, supported by cross-cutting governance mechanisms.

This layered design reflects the growing recognition that smart transportation technologies must be embedded within coherent architectures to deliver resilience benefits. Prior studies emphasize that fragmented implementations of digital technologies often fail to translate intelligence into effective operational responses ([Esangbedo et al., 2024](#)). By contrast, the proposed architecture aligns data acquisition, decision intelligence and control actions within a unified framework, enabling transportation systems to respond dynamically to disruptions.

3.2 Sensing and data layer: enabling situational awareness

The sensing and data layer forms the foundation of the smart resilient transportation architecture. As shown in [Figure 1](#), this layer comprises IoT sensors, traffic detectors, connected vehicles, vehicle to infrastructure communication and freight tracking technologies. These components generate continuous streams of real-time and historical data on traffic flows, infrastructure conditions, vehicle movements and logistics operations.

Extensive research demonstrates that situational awareness is a prerequisite for both smart operation and resilience ([Afriyie et al., 2019](#); [Kaber and Endsley, 2004](#)). In resilience

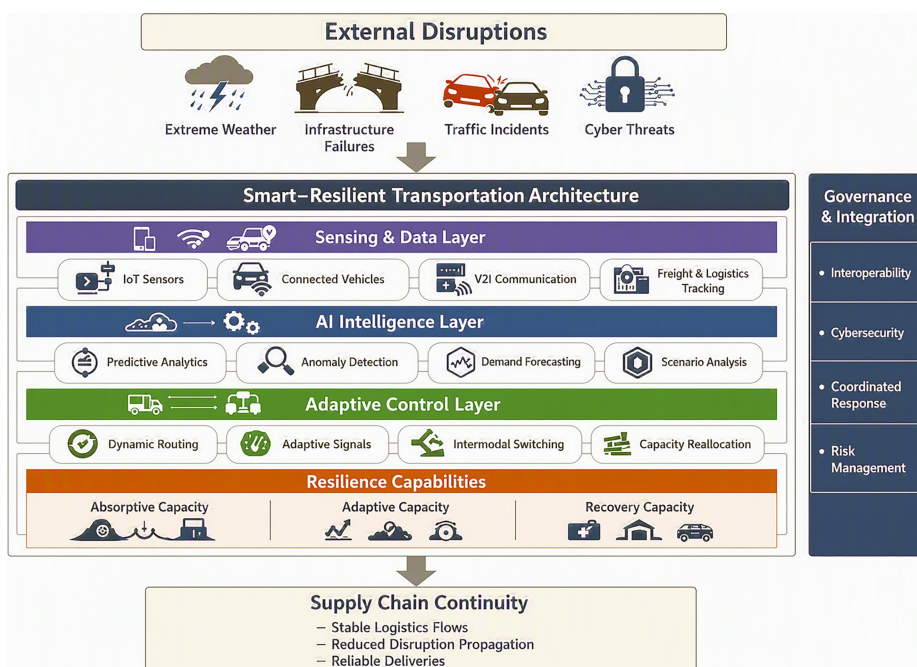


Figure 1. Smart resilient transportation architecture enabling supply chain continuity

Source: Author's conceptual synthesis

contexts, early detection of abnormal patterns such as sudden congestion, infrastructure stress or capacity bottlenecks enhances absorptive capacity by allowing systems to respond before disruptions escalate. Importantly, the resilience value of this layer depends not only on data volume but also on data integration across modes and assets, reducing informational silos that hinder coordinated responses during disruptions.

3.3 AI intelligence layer: from data to predictive and prescriptive insight

The AI intelligence layer transforms raw transportation data into predictive and prescriptive insights that support adaptive decision-making (Mustafeez ur rehman *et al.*, 2025). As depicted in Figure 1, this layer includes machine learning models for traffic flow prediction, anomaly detection, demand capacity forecasting and scenario evaluation. Neural networks, deep learning and hybrid AI approaches have been widely applied to transportation systems to anticipate congestion, detect incidents and optimize operations (Nasiri *et al.*, 2020; Zemmouchi-Ghomari, 2025).

From a resilience perspective, AI enhances adaptive capacity by enabling transportation systems to move beyond reactive control. Predictive analytics support absorptive capacity by anticipating system stress, while learning algorithms enable continuous improvement based on past disruptions (Ivanov and Dolgui, 2021). However, prior research cautions that AI benefits remain limited when intelligence is not structurally linked to operational control (Xie *et al.*, 2026). This insight reinforces the need for architectural integration between intelligence and control layers.

3.4 Illustrative AI applications for transportation resilience

The resilience value of AI can be further illustrated through specific transportation applications (see [Table 2](#)). For example, machine-learning-based traffic prediction models can identify congestion risks and capacity bottlenecks before they disrupt network performance, thereby supporting absorptive capacity. Anomaly detection algorithms can continuously monitor infrastructure conditions and identify abnormal patterns associated with equipment failures, cyber incidents or traffic disturbances. Reinforcement learning approaches can support adaptive routing decisions by dynamically identifying alternative transportation paths during disruptions. Similarly, AI-driven demand forecasting models can improve freight planning and capacity allocation by anticipating fluctuations in transportation demand. Digital twin technologies can further enhance resilience by simulating disruption scenarios and evaluating alternative response strategies before implementation. Collectively, these applications demonstrate how AI contributes to anticipation, adaptation and recovery processes within resilient transportation systems.

3.5 Adaptive control layer: translating intelligence into system action

The adaptive control layer operationalizes AI-generated insights by translating them into real-time system actions ([Agarwal et al., 2020](#)). As illustrated in [Figure 1](#), this layer includes dynamic routing, adaptive signal control, intermodal switching, capacity reallocation and redundancy activation mechanisms. These functions enable transportation systems to adjust network configurations and operational strategies in response to evolving disruption conditions.

Adaptive control is central to resilience because it determines whether intelligence leads to meaningful performance outcomes. Empirical studies show that flexible routing and control mechanisms significantly reduce disruption impacts by preventing localized failures from propagating across networks ([El Baz and Ruel, 2024](#); [Esangbedo et al., 2024](#)). By embedding adaptive control within the architecture, the proposed framework ensures that smart technologies directly support resilience rather than remaining confined to decision support tools.

3.6 Resilience capabilities as emergent system properties

The interaction of the sensing, intelligence and control layers gives rise to resilience capabilities, which constitute the fourth layer of the architecture in [Figure 1](#). These capabilities absorptive, adaptive and recovery capacity are treated as emergent properties of integrated system design rather than as isolated measures. Absorptive capacity is supported by early detection and redundancy, adaptive capacity by intelligent control and flexibility and recovery capacity by coordinated reconfiguration and learning.

This perspective aligns with resilience theory in complex systems, which emphasizes adaptability and learning over static robustness ([Ponomarov and Holcomb, 2009](#)). Transportation systems that lack integration across layers may exhibit smart features without resilience or resilience measures without intelligence. The proposed architecture addresses this limitation by explicitly linking each layer to specific resilience mechanisms.

3.7 Governance and integration across architectural layers

[Figure 1](#) highlights governance and integration as a cross-cutting element that supports all architectural layers. Governance mechanisms include interoperability standards, cybersecurity safeguards and institutional coordination across transportation modes and organizations. Prior research emphasizes that resilience failures often stem from organizational fragmentation rather than technical shortcomings ([Xie et al., 2026](#)).

Table 2. AI applications supporting transportation resilience

AI technique	Transportation application	Resilience function	Resilience capacity supported
Machine learning	Traffic flow prediction	Early disruption identification	Absorptive capacity
Anomaly detection	Infrastructure monitoring	Failure and incident detection	Absorptive capacity
Reinforcement learning	Dynamic routing	Adaptive network reconfiguration	Adaptive capacity
Demand forecasting	Freight and capacity planning	Resource optimization	Adaptive capacity
Digital twins	Scenario simulation	Evaluation of response alternatives	Recovery capacity
Predictive analytics	Infrastructure risk forecasting	Anticipatory decision-making	Absorptive and adaptive capacity
AI-based learning systems	Postdisruption analysis	Continuous improvement	Recovery capacity
Source(s): Author's synthesis based on transportation resilience and intelligent transportation systems literature			

As transportation systems become increasingly digital and interconnected, cybersecurity emerges as a critical component of resilience. Governance structures must therefore ensure secure data exchange and coordinated decision-making, particularly during crisis situations. By embedding governance within the architecture, the framework recognizes resilience as both a technical and institutional challenge.

At the operational level, governance can be implemented through transportation coordination centers that integrate data, decision-making and communication across transportation agencies, infrastructure operators, logistics providers and emergency response organizations. During disruption events, predefined decision authority structures can facilitate rapid response by assigning responsibility for traffic management, resource allocation, infrastructure prioritization and intermodal coordination. Shared data platforms and interoperability standards enable participating organizations to maintain a common operating picture and exchange real-time information regarding network conditions, available capacity and recovery priorities. Cross-modal coordination committees can further support joint decision-making when disruptions affect multiple transportation modes simultaneously. In addition, incident response protocols and cybersecurity governance frameworks should establish clear procedures for disruption escalation, information sharing and recovery coordination. These mechanisms help translate governance from a conceptual principle into an operational capability that supports adaptive and resilient transportation system performance.

3.8 Supply chain continuity as a downstream outcome

Consistent with the transportation-centric focus of this study, supply chain continuity is positioned as a downstream outcome of transportation system performance rather than as an architectural component. As shown in [Figure 1](#), resilient transportation systems stabilize physical flows, reduce disruption propagation and support delivery reliability and lead time stability across supply chains ([Craighead et al., 2007](#); [Ivanov and Dolgui, 2020](#)).

This framing preserves analytical clarity while demonstrating the broader systemic relevance of smart resilient transportation architectures. Supply chain continuity emerges not from firm-level interventions alone but from the ability of transportation systems to maintain functionality under disruption.

4. Strategic pathways for supply chain continuity

Building on the smart resilient transportation architecture presented in [Figure 1](#), this section explains how transportation systems enable supply chain continuity through distinct strategic pathways under disruption conditions. Rather than treating continuity as a firm-level or managerial outcome, the analysis demonstrates how continuity emerges from the coordinated operation of sensing, AI-driven intelligence, adaptive control and resilience capabilities embedded within transportation system architectures. Three interrelated pathways are identified: predictive resilience, adaptive network reconfiguration and coordinated recovery.

4.1 Predictive resilience under anticipated disruptions

The first pathway emphasizes predictive resilience, which enables transportation systems to anticipate disruptions and mitigate their impacts before severe performance degradation occurs ([Katsaliaki et al., 2022](#)). As illustrated in [Figure 1](#), this pathway is primarily enabled by the interaction between the sensing and data layer and the AI intelligence layer. Continuous monitoring of traffic conditions, infrastructure health, weather patterns and

freight movements generates early warning signals that can be processed through predictive analytics and machine learning models.

Prior research shows that predictive capabilities significantly enhance system robustness by allowing transportation operators to act proactively rather than reactively (Kaber and Endsley, 2004; Zemmouchi-Ghomari, 2025). In the context of supply chain continuity, predictive resilience supports delivery reliability and lead time stability by enabling early rerouting, capacity adjustments and schedule modifications. These anticipatory actions strengthen absorptive capacity and reduce the likelihood that localized transportation disruptions propagate across supply chains (Craighead *et al.*, 2007; Ivanov and Dolgui, 2020).

4.2 Adaptive network reconfiguration during active disruptions

The second pathway focuses on adaptive network reconfiguration, which becomes critical once disruptions materialize. As shown in Figure 1, this pathway relies on the integration of the AI intelligence layer with the adaptive control layer, where real-time insights are translated into operational actions. Transportation disruptions such as infrastructure failures, accidents or sudden demand surges often render static routing and scheduling strategies ineffective.

Adaptive control mechanisms including dynamic routing, intermodal switching and resource reallocation allow transportation systems to reconfigure network operations in response to evolving conditions. Empirical studies indicate that such flexibility significantly reduces disruption impacts by preventing congestion and capacity failures from cascading through the network (Esangbedo *et al.*, 2024; El Baz and Ruel, 2024). From a supply chain perspective, adaptive reconfiguration preserves the continuity of physical flows even when preferred routes or modes become unavailable, reinforcing the central role of adaptive capacity in resilient transportation systems.

4.3 Coordinated recovery and restoration of transportation functionality

The third pathway addresses coordinated recovery, which governs how transportation systems restore functionality following disruptions. As depicted in Figure 1, recovery capacity emerges from the combined operation of adaptive control mechanisms and resilience capabilities, supported by governance and integration structures. Recovery involves not only physical infrastructure repair but also the strategic prioritization and coordination of network resources.

Research on transportation resilience highlights that recovery speed and coordination are critical determinants of overall system resilience (Cheng and Yang, 2017; Xie *et al.*, 2026). For supply chains, prolonged recovery periods translate directly into sustained delivery delays and inventory imbalances. Transportation systems that can rapidly reallocate capacity, restore critical links and synchronize recovery actions across modes enable faster normalization of logistics flows. AI-driven learning further strengthens recovery capacity by incorporating postdisruption data into future decision-making processes (Ivanov and Dolgui, 2021).

4.4 Illustrative disruption scenario: extreme weather impact on freight corridors

To demonstrate the practical operation of the proposed architecture, this subsection presents an illustrative disruption scenario involving severe weather conditions affecting a major freight transportation corridor. Extreme weather events such as flooding, snowstorms and hurricanes have increasingly disrupted transportation infrastructure, reducing network capacity and threatening supply chain continuity (Esangbedo *et al.*, 2024).

In the scenario, severe flooding affects a critical road and rail corridor responsible for serving a regional logistics hub. Real-time information collected through IoT sensors, infrastructure monitoring systems, connected vehicles and freight tracking platforms identifies abnormal traffic conditions, infrastructure stress and declining transportation capacity. These data are transmitted to the AI intelligence layer, where predictive analytics and anomaly detection models estimate the duration of the disruption, identify vulnerable network segments and forecast congestion levels across alternative routes.

Based on these predictions, the adaptive control layer activates dynamic routing mechanisms, reallocates available transportation capacity and initiates intermodal switching from road transport to rail or alternative freight corridors where feasible. Transportation operators prioritize essential freight movements, including medical supplies, food products and time-sensitive shipments, to minimize disruption impacts (Nguyen *et al.*, 2021). Simultaneously, governance and coordination mechanisms facilitate information sharing among transportation agencies, logistics providers, infrastructure operators and emergency management authorities.

As weather conditions improve, recovery actions are initiated to restore damaged infrastructure and normalize transportation operations. Data generated throughout the disruption are retained within the system and used to refine future predictive models and response strategies. This scenario illustrates how sensing, intelligence, adaptive control and governance mechanisms interact to support absorptive, adaptive and recovery capacities within resilient transportation systems.

It should be noted that this scenario is intended to illustrate the operational logic of the proposed architecture rather than provide empirical validation. Future research may use digital twins, agent-based simulation, discrete-event simulation or real-world transportation data sets to quantitatively evaluate the effectiveness of alternative architectural configurations under different disruption conditions.

4.5 *Linking transportation capabilities to supply chain continuity outcomes*

While the proposed architecture remains transportation centric, its implications for supply chain continuity can be clarified by explicitly linking transportation capabilities to continuity outcomes. Table 3 summarizes how the smart resilient transportation capabilities illustrated in Figure 1 translate into specific supply chain continuity effects. This mapping reinforces the argument that continuity emerges from transportation system performance rather than from isolated firm-level interventions.

Table 3. Smart resilient transportation capabilities and supply chain continuity outcomes

Transportation architecture layer	Key capability	Primary transportation function	Supply chain continuity outcome
Sensing and data layer	Real time visibility	Early disruption detection	Reduced uncertainty
AI intelligence layer	Predictive analytics	Anticipation of capacity shortfalls	Lead time stability
Adaptive control layer	Dynamic routing	Network reconfiguration	Delivery reliability
Resilience capabilities	Absorptive and recovery capacity	Rapid service restoration	Continuity of logistics flows
Governance and integration	Interoperability and coordination	Cross modal alignment	Network robustness
Source(s): Author’s conceptual synthesis			

4.6 Synthesis of strategic pathways

Taken together, the three pathways illustrate how supply chain continuity emerges as a systemic outcome of smart resilient transportation design. Predictive resilience stabilizes flows before disruptions escalate, adaptive reconfiguration maintains functionality during active disturbances and coordinated recovery accelerates postdisruption restoration. By explicitly linking these pathways to the architectural layers presented in [Figure 1](#), this section demonstrates how transportation systems serve as foundational enablers of continuity in increasingly volatile environments.

5. Managerial and policy implications

The smart resilient transportation architecture developed in this study has important implications for transportation managers, infrastructure operators and policymakers seeking to enhance system resilience and supply chain continuity. By emphasizing architectural integration rather than isolated technology adoption, the framework provides actionable guidance on how transportation systems can be designed, operated and governed to perform reliably under disruption conditions.

5.1 Implications for transportation authorities and infrastructure operators

For transportation authorities and infrastructure operators, the findings highlight the need to shift from fragmented digital initiatives toward integrated system architectures. Investments in sensors, data platforms or AI tools generate limited resilience benefits when implemented independently. Managers should instead prioritize the alignment of sensing, intelligence and adaptive control mechanisms so that predictive insights can be translated into timely operational actions. This requires rethinking operational protocols to support dynamic routing, intermodal coordination and rapid capacity reallocation during abnormal conditions.

The framework also suggests that performance evaluation should extend beyond efficiency metrics such as travel time or throughput. Incorporating resilience-oriented indicators such as recovery time, adaptability under stress and continuity of service can better reflect system performance in volatile environments ([Cheng and Yang, 2017](#); [Esangbedo et al., 2024](#)). Embedding such metrics into routine management practices encourages resilience by design rather than reactive crisis management.

5.2 Implications for logistics and supply chain stakeholders

Although the proposed architecture remains transportation centric, it carries clear implications for logistics and supply chain stakeholders who depend on transportation system performance. The framework clarifies that supply chain continuity is largely shaped by the resilience of transportation networks rather than by firm-level contingency measures alone. Logistics managers should therefore engage more actively with transportation authorities and infrastructure operators to align continuity planning efforts.

Participation in data-sharing platforms, collaborative planning initiatives and intermodal coordination mechanisms can enhance visibility and responsiveness during disruptions. Rather than treating transportation risks as exogenous constraints, supply chain actors can leverage smart resilient transportation systems as strategic assets that stabilize logistics flows and reduce disruption propagation ([Craighead et al., 2007](#); [Ivanov and Dolgui, 2020](#)).

5.3 Implications for policymakers and regulators

For policymakers and regulators, the proposed architecture underscores the importance of system-level policy frameworks that support integration and coordination across

transportation modes and institutions. Policies promoting interoperability standards, open data exchange and cross-agency collaboration are essential for enabling the architectural integration illustrated in [Figure 1](#). Without such support, smart transportation initiatives risk reinforcing organizational silos that undermine resilience.

The framework also suggests that resilience should be explicitly incorporated into transportation planning and investment appraisal. Evaluating projects based on their contribution to adaptive and recovery capacity rather than solely on cost efficiency aligns transportation policy with broader objectives related to economic continuity and risk reduction ([Xie et al., 2026](#)). Cybersecurity regulation similarly emerges as a critical policy concern as transportation systems become increasingly digital and interconnected.

5.4 Governance and institutional coordination

A central implication of the framework is the role of governance as an enabler of resilience. Effective smart resilient transportation architectures require institutional arrangements that facilitate coordination across jurisdictions, modes and organizations, particularly during disruption events. Clear decision authority, shared situational awareness and predefined coordination protocols reduce response delays and improve recovery outcomes.

By embedding governance considerations within the architecture, the framework emphasizes that resilience is not purely a technical challenge but also an institutional one. Policymakers and system operators should therefore treat governance design as an integral component of smart resilient transportation systems rather than as an external policy overlay.

6. Future research directions and boundary conditions

The smart resilient transportation architecture proposed in this study provides a foundation for future research on the integration of digital intelligence, adaptive capacity and resilience in transportation systems. While the framework is conceptual in nature, it highlights several promising directions for empirical, methodological and comparative research that can advance understanding of how transportation systems enable continuity under disruption conditions.

6.1 Empirical validation and measurement

Future research should empirically examine the relationships among the architectural layers presented in [Figure 1](#). Quantitative studies using data from ITS, traffic management centers or freight transportation networks could assess how the integration of sensing, AI-driven intelligence and adaptive control influences resilience outcomes such as recovery time, service continuity and network robustness. Longitudinal designs would be particularly valuable for capturing how adaptive capacity evolves over repeated disruption events and how learning mechanisms improve system performance over time.

6.2 Simulation- and scenario-based approaches

Simulation-based methods offer significant potential for extending this research. Digital twins, agent-based models and scenario analysis can be used to operationalize the proposed architecture and evaluate system behavior under extreme or rare disruption scenarios. Such approaches enable controlled experimentation with different architectural configurations, allowing researchers to explore trade-offs between efficiency and resilience that are difficult to observe in real-world settings. Simulation studies can also support policy evaluation by testing alternative investment and governance strategies.

6.3 Cross-modal and contextual comparisons

The proposed architecture is intentionally generic and may be applied across different transportation modes, including road, rail, maritime and intermodal systems. Future research should examine how architectural priorities vary across modes, particularly with respect to data availability, control flexibility and recovery dynamics. Comparative studies across geographic regions and institutional contexts would further illuminate how governance structures and regulatory environments shape the effectiveness of smart resilient transportation systems.

6.4 Boundary conditions of the framework

Several boundary conditions should be acknowledged. First, the framework is most applicable to data-rich transportation environments where sensing infrastructure and digital connectivity are sufficiently developed. In data-poor or resource-constrained contexts, the feasibility of AI-driven intelligence and adaptive control may be limited. Second, the architecture assumes a minimum level of institutional coordination and governance capacity; fragmented or highly decentralized systems may face challenges in achieving the level of integration required for resilience. Finally, the framework focuses on system-level transportation performance and does not explicitly model firm-level supply chain decision-making, which may moderate continuity outcomes in certain contexts.

7. Conclusion

Transportation systems are operating in an environment characterized by growing uncertainty, increasing connectivity and more frequent disruptions. In this context, maintaining continuity requires more than investments in digital technologies or traditional resilience measures alone. The analysis presented in this study suggests that transportation resilience depends on how sensing capabilities, intelligent analytics, adaptive operational responses and governance arrangements work together within an integrated system. When these elements are aligned, transportation networks become better able to identify emerging risks, adjust to changing conditions and restore functionality following disruption events. This integrated perspective provides a more comprehensive understanding of how transportation systems can remain reliable and responsive while continuing to support the movement of goods across supply chains.

By adopting a multilayer transportation systems perspective, the study clarifies how digital intelligence contributes to resilience only when it is structurally linked to adaptive operational mechanisms. The proposed architecture, illustrated in [Figure 1](#), demonstrates how predictive capabilities support anticipation, adaptive control enables real-time reconfiguration and coordinated recovery restores functionality following disruptions. Within this framework, supply chain continuity is positioned as a downstream outcome of transportation system performance, preserving a transportation-centric analytical focus while highlighting broader systemic implications.

Beyond its theoretical implications, the proposed architecture provides a structured way of understanding how transportation systems can remain operational during periods of disruption. By emphasizing the interaction among sensing capabilities, intelligent analytics, adaptive control mechanisms and governance structures, the framework highlights the conditions under which transportation networks can sustain service continuity and support broader logistics performance.

From a practical perspective, the findings underscore the importance of moving beyond fragmented technology adoption toward integrated system architectures supported by effective governance and coordination. Transportation authorities,

infrastructure operators and policymakers are encouraged to evaluate transportation systems not only in terms of efficiency but also in terms of adaptability, recovery speed and continuity under stress.

In an era of increasing uncertainty and disruption, the proposed smart resilient transportation architecture provides a coherent conceptual foundation for understanding how transportation systems can be designed to remain functional, adaptive and reliable. By positioning resilience as an architectural outcome rather than an afterthought, this study offers a valuable framework for both researchers and practitioners seeking to strengthen transportation systems and the supply chains that depend on them.

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