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Designing Resilience for Multi-System Dynamics of Future Transportation

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Abstract: The transition from fossil-fuel-based transportation systems to those reliant on lowand zero-emission technologies marks a crucial paradigm shift, necessitating a reevaluation of resilience metrics and strategies. As infrastructure investments adapt to a changing climate and the risk of extreme events, our paper identifies the complexities of resilience within the transportation sector, which now integrates a broad array of energy sources like electricity, hydrogen, and synthetic fuels. This deepening integration increases the complexity of maintaining transportation resilience, highlighting the inadequacy of traditional resilience metrics designed for centralized systems under stable climate conditions. We propose a Multi-System Dynamics (MSD) framework to develop new, system-level resilience metrics to effectively manage emerging risks associated with diverse energy sources and extreme weather conditions. This study emphasizes the need for robust scenario analysis and the integration of Cost-Benefit Analysis (CBA) tools that account for resilience, offering a framework to evaluate the economic impacts and benefits of resilience investments. Our proposed approach encompasses evaluating resilience at the system level to identify and mitigate new risks introduced by the adoption of low-carbon technologies and the interconnectedness of modern energy and transportation infrastructures. Through rigorous scenario analysis, we aim to support robust decision-making that can withstand and adapt to the unpredictabilities of a low-carbon future. By advancing these areas, the paper contributes to the strategic planning necessary to foster a resilient, sustainable transportation ecosystem capable of facing both current and future challenges.

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1. Introduction

A global shift towards sustainable transportation is characterized by a move away from predominantly fossil-fuel-based drivetrains to a diverse array of low- and zero-emission technologies, as well as changes in mobility patterns. This implies an increasing reliance upon direct electrification and a greater mix of carbon-neutral alternative fuels for all vehicles that move passengers or freight across all modes of transportation. In addition to electricity, hydrogen (European Commission, 2018; IPCC, 2023), ammonia, methanol, biofuels, and synthetic fuels (also called power-to-gas/liquids/fuels or electro fuels, generally referred to as carbon-based fuels produced from carbon dioxide (CO_2) and water, with (renewable) electricity as the primary source of energy (Brynolf *et al.*, 2022)) are all potential fuel sources. The reliance on these new fuel sources will fundamentally alter the relationship between energy supply and transportation demand (Daniels & Yeh, 2022; Ueckerdt *et al.*, 2021). This shift offers opportunities to diversify fuel supply and production, enhance demand-side management through strategies such as smart charging and vehicle-to-grid services (Heinisch *et al.*, 2021), and advance energy storage technologies that benefit both transportation and energy systems (Levin *et al.*, 2023). However, disruptions in energy supply that impact the operational capacity and performance of these new transportation networks (Nguyen *et al.*, 2022; Sovacool & Mukherjee, 2011) will be unlike anything previously experienced. This paradigm shift calls for a reevaluation of energy resilience within the transportation sector.

For example, the start of 2024 underscored the inherent challenges in shifting toward sustainable transportation. A severe snowstorm on January 3 left thousands stranded for up to 19 hours on southern Sweden's E22 highway, many in electric vehicles (EVs) with no way to charge them. January's extreme cold in the United States from Chicago to northern Texas made life painful for EV owners, with reduced driving range and hours of waiting at charging stations due to non-functioning chargers and non-charging cars due to the cold. In addition to these cold-weather EV challenges, increasing blackouts from severe weather and wildfires highlight the difficulties of accommodating low-carbon transportation (Verschuur *et al.*, 2024). Beyond weather, recent shipping mishaps in the Suez Canal and the Port of Baltimore expose global supply chain vulnerabilities (Izaguirre *et al.*, 2021; Verschuur *et al.*, 2022; Verschuur, Koks, & Hall, 2023; Verschuur, Koks, Li, & Hall, 2023). The advent of new fuels like ammonia and hydrogen introduces risks unfamiliar to suppliers, consumers, and first responders, compounded by material shortages and power outages (Verschuur *et al.*, 2024).

Extreme weather events are likely to intensify in the future with changing climate (IPCC, 2023). Changes in temperature, precipitation, sea level, and coastal storms will increase the vulnerability of transportation infrastructure (Neumann *et al.*, 2015, 2021). The existing approaches cover only a small portion of expected transportation infrastructure sector effects from climate change. There is a need for a holistic, longer-term approach to managing and planning transportation infrastructure to incorporate climate change considerations and environmental and social impacts (Schweikert *et al.*, 2014, 2015). It is important to reassess vulnerability and risk of existing infrastructure in light of changing climate, and to look forward to likely changes in climate and extreme events in upgrading or planning new infrastructure for road, rail, and air transportation systems, as well as electric and telecommunications networks.

These considerations spotlight the fragile underpinnings of future transportation systems and the critical need for a resilient support network, including accessible refueling stations, reliable power grids, and versatile energy infrastructure. Addressing these complexities is vital for the reliability and sustainability of low-carbon transportation, yet traditional resilience metrics, reflecting centralized fossil fuel systems, do not sufficiently encompass the complexities and environmental concerns across the entire value chain of decentralized energy systems. Hence, there is a pressing need to complement and revise traditional resilience metrics developed for fossil-based fuels, such as petroleum strategic reserves (McCarthy *et al.*, 2007) and energy independence/security measures (Esfahani *et al.*, 2021).

1.1 General Concepts of Resilience

A broadly-applicable concept of resilience has been developed within the context of risk management. Risk is conceptually defined as:

$$Risk = HazardLikelihood \times Vulnerability \times Consequences$$

Where *Risk* represents the expected losses to the economy and society from disruptions in transportation functionality due to natural hazards. *Hazard Likelihood* refers to the probabilities associated with relevant natural hazards. *Vulnerability* assesses how susceptible assets are to these natural hazards. *Consequences* encompass the impact of asset destruction or service disruptions, including losses incurred by asset owners, users, and the wider community.

Fig 1 identifies the concepts of reliability, risk, and resilience across the four analytic elements of a human-caused or natural hazard: the hazard is initiated with some likelihood of occurrence, it impinges upon an object or system with some probability of causing it to reach a "limit state" in which functionality is jeopardized (this probability is also known as vulnerability), reaching the limit state results in a set of identifiable negative consequences, and finally, the functionality is recovered and service is restored (National Academies of Sciences, Engineering & Medicine, 2021;

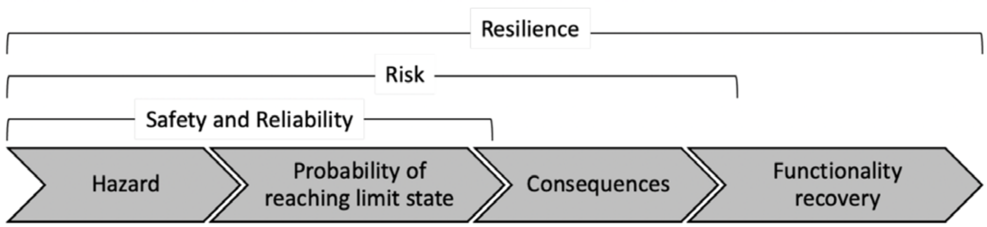

Figure 1. The resilience framework, incorporating safety and reliability within the broader context of risk management. "Limit state" refers to the threshold beyond which the system fails to function correctly. Source: National Academies of Sciences, Engineering and Medicine (2021).

Sambasivam *et al.*, 2024; Willis & Loa, 2020). Implicit in this resilience framework is the identification both of the object of analysis, including its provided service and limit state, and of the hazard (or ensemble of hazards). Applied to the transportation system, the object could be a discrete element of critical infrastructure, such as a bridge or tunnel, a key resource, such as communications or energy, a subsystem or even the transportation system itself. While the hazard could be a specific event, such as an earthquake or sabotage, one would want the transportation system of the future to be resilient across all hazards, both the regularly occurring and the rare and unpredictable.

While the disciplines of safety and reliability focus on reducing vulnerabilities, and risk management puts that in the context of consequences, resilience captures both the capacity to withstand and to recover from disruptive events. Resilience emphasizes two critical components: service continuity and system recovery. Service continuity is the ability to maintain essential functions during an adverse event, while system recovery refers to the process of returning to a normal or an improved state afterwards. **Fig 2** illustrates functionality recovery curve connecting four key concepts in resilience research: reliability, vulnerability, survivability, and recoverability. The disruption reduces the ability of the system to maintain its level of service, though perhaps not entirely, and after the disruptive event it takes some time to restore the system to an acceptable level of service again. Note that the system may not completely regain its pre-hazard level of service, even after recovery, either because of permanent damage caused by the disruption or because of adaptation or other reconfiguration of the system (Amoaning-Yankson & Amekudzi-Kennedy, 2017). Functionality recovery curves and their associated resilience metrics, while not widely adopted in practice, provide a valuable foundation for analyzing the resilience of transportation systems to natural- or man-made hazards. These concepts are instrumental in structuring the analysis described in the assessment framework described below. Yet, further research is necessary to enhance the application and utility of these metrics (National Academies of Sciences, Engineering & Medicine, 2021).

The concept of resilience is related to the adjacent concept of robustness by uncertainty. The discipline of risk management, from which these concepts around resilience are drawn, is inextricably linked with uncertainty. The underlying elements of risk and resilience are inherently uncertain. For example, the likelihood of a hazard being initiated in the future may be statistically predictable based on historical occurrences, but for many of the most consequential hazards the timing is unknown and the likelihood may change over time in a way that is not easily observable. The ensemble of hazards may shift over time as well, as technology and social priorities change. The vulnerability of a complex system can rarely be tested empirically, though the recent

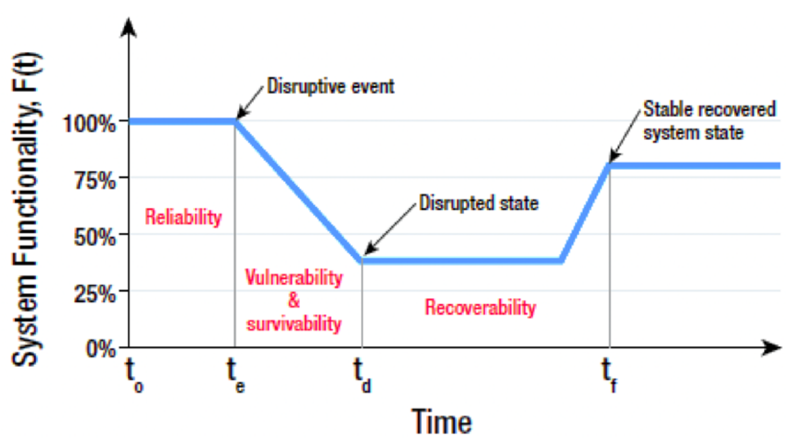

Figure 2. Functionality recovery curve in resilience research.

example of the 2024 earthquake in Taiwan illustrates that prior exposure of a system to a hazard can lead to reduced vulnerability and increased resilience. Consequences are rarely one-dimensional. The insurance industry, for example, follows actuarial principles to monetize different types of consequences and limit exposure to any consequences that cannot be monetized. This is harder to do when the system is complex and the range of potential hazards is inclusive, such as for the energy or transportation systems. Finally, the system itself may evolve in an uncertain way into the future, so that a system that is more resilient today may become less resilient in the future, or vice versa, simply because of organic system growth. In the midst of this uncertainty, any system with features or capabilities that lead to maintaining a relatively high level of resilience across a range of potential future states is considered to be robust (Rodriguez-Matas *et al.*, 2024). Thus, we seek to achieve a resilient and robust transportation system, that is, one in which the system remains resilient across a range of different potential futures.

1.2 Multi-System Dynamics (MSD) in Transportation

The transportation system, which governs the movement of passengers and freight, can be conceptualized within a Multi-System/Multi-Sector Dynamics (MSD) framework as a "system of systems." Transportation can be separated into three distinct subsystems (**Fig 3**). The purpose of the transportation system is to move people and goods to their destinations. Vehicle flows—automobiles, trucks, trains, ships, airplanes, etc.—make up the operational dynamics, where the choice of mode influences the pattern and volume of vehicle flows (Rodrigue, 2020). Vehicle movements are supported by a system of largely fixed physical infrastructure, tangible assets like roadways, rail tracks, ports, and airports, along with the sometimes intangible support systems necessary for their operation and maintenance. Each of these three transportation subsystems has unique characteristics and features. For example, the mobility and logistics layer can be represented as a directed graph, moving people and goods from origins to destinations, while the vehicle flow system has closed loops representing vehicle round-trips and no net vehicle relocation over time. And each of the three subsystems could be decomposed further into more narrowly-prescribed subsystems, such as on-road freight, for example. Though each transportation subsystem can be evaluated individually, shared resources (i.e., transportation or energy infrastructure) and the potential for substitution (i.e., mode choice) link the subsectors together, requiring a multi-system dynamics approach to understand the transportation sector.

The complexity and interconnected nature of the transportation and energy systems requires a multi-sector dynamic approach, where the whole is not simply a collection of independent elements but a dynamic network. The MSD approach recognizes that system properties, such as resilience, may not be simply inherited from the comprising subsystems but might be instead emergent at the multi-system level; or, conversely, disruptions in one subsystem can have cascading effects throughout the system. For instance, a severe weather event could impede the production of biofuels, affect the transportation of goods, or hinder the mobility of the workforce necessary for the operation of energy systems. At the same time, the increase in distributed generation and shift away from a centralized power system topology provides both opportunities for greater resilience and challenges of its own. As the energy system reconfigures itself to limit carbon emissions, the MSD approach prompts us to envision how alternative energy systems and technologies may change the resiliency landscape.

Yet, technological maturity and integration within existing infrastructures remain uncertain, highlighting the need for

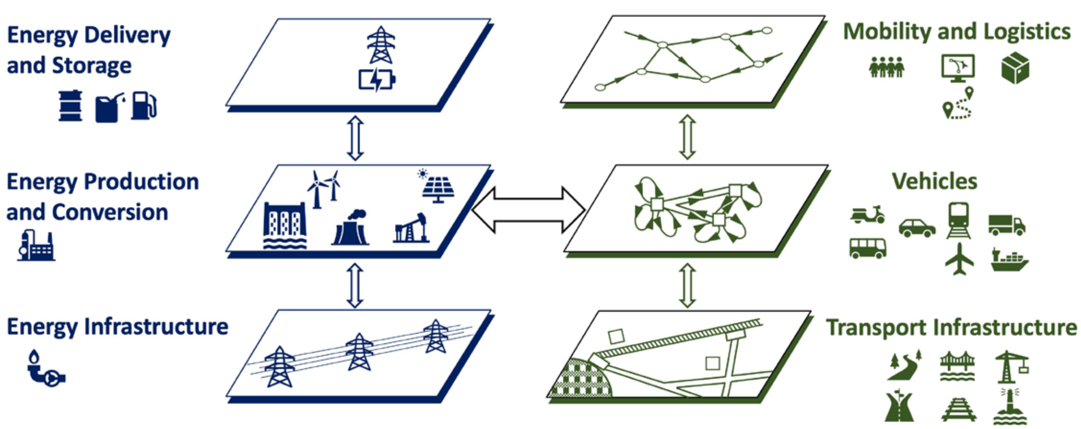

Figure 3. Integrated Framework of the transportation System within a Multi-System Dynamics (MSD) Perspective. This schematic illustrates the transportation system as system composed of various subsystems: mobility and logistics, vehicles, and transportation infrastructure in green, and the energy system in blue. The black arrow indicates strong bi-directional interactions within the Multi-System Dynamics of future transportation. Figure adapted from (Wandel *et al.*, 1991).

flexible and robust resilience strategies. The pace at which electric vehicles (EVs), hydrogen fuel cells, and synthetic fuels can replace conventional fossil fuels depends on advancements in technology, reductions in costs, and the establishment of supportive infrastructures (Brynolf *et al.*, 2022; Grahn *et al.*, 2022; Millinger *et al.*, 2023; Muratori *et al.*, 2021; Ueckerdt *et al.*, 2021). Moreover, the variability in consumer adoption rates, influenced by policy measures, pricing structures, and societal acceptance, further complicates predictions for the future transportation landscape (IPCC, 2023; Yeh *et al.*, 2022).

Within the MSD framework, these complexities and uncertainties challenge our traditional understanding of system resilience. MSD in transportation focuses on the interrelationships and evolutions within various transportation systems in response to technological advances and changing demands, emphasizing the interconnections of transportation systems with broader energy and societal systems. This interdependence means that disruptions in one part of the system can have cascading effects, and any analysis of resilience must therefore account for the complexities of system integration and the interplay between

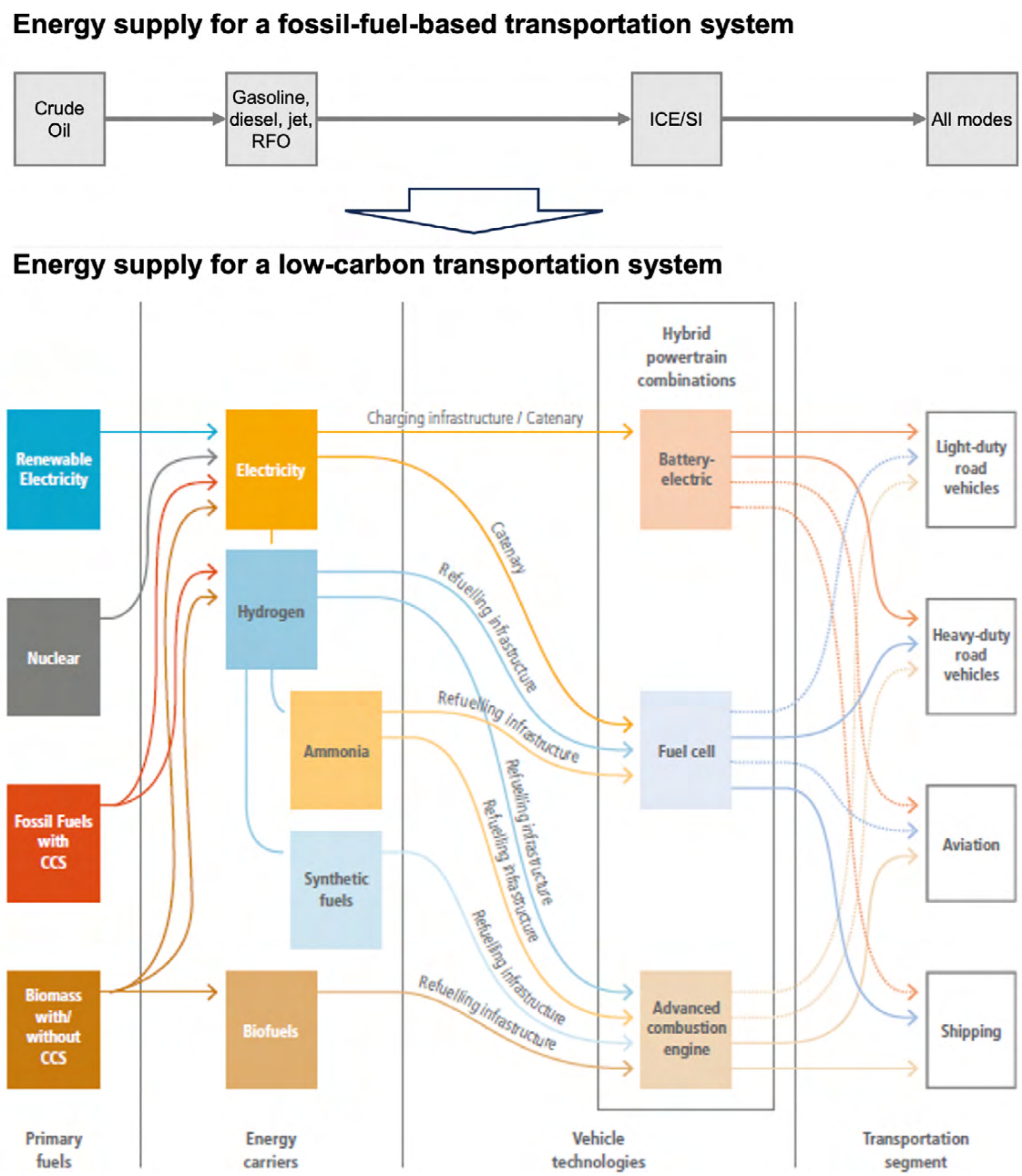

Figure 4. Changes to the energy system required by the transition to a low-carbon transportation system. Primary energy sources are shown in the far left, while the segments of the transportation system are in the far right. Energy carriers and vehicle technologies are represented in the middle. Top panel shows the fossil-fuel dependent transportation system since 1990, and the bottom shows the Multi-System Dynamics of future transportation after 2020. Source: Modified from Shaw *et al.* (2022)

different sectors. Addressing these system interactions requires a multidisciplinary effort, combining insights from technology development, policy analysis, and social sciences to forge pathways toward a resilient and sustainable transportation future.

In this paper, we explore the changing nature of resilience for the transportation sector as it transitions to a fossil-free future. The shift from fossil fuels to a diverse array of lowcarbon alternatives brings significant changes across the entire supply chain—from fuel production, delivery, and storage to utilization, as well as transformations in the business models that govern transportation services. Understanding these shifts is crucial, as they present both challenges and opportunities with profound, long-lasting impacts, demanding strategic planning across multiple decades. Our objective is to initiate a discussion about new resilience metrics that are applicable to low-carbon transportation systems. These metrics are intended to effectively identify risks, minimize vulnerabilities, and address potential systemic weaknesses that will be necessary to support a fossil-free transportation future.

2. Necessary Research to Strengthen Transportation Resilience

2.1 Assessment Methodologies in Resilience Investment

Resilience, like reliability, is a relative measure. One may reasonably compare two similar systems in terms of their relative resilience across a range of hazards, and one could measure the relative increase or decrease in the resilience of a system over time. Yet, since one takes concrete steps to increase resilience, and these steps require the use of limited resources, one would like to know whether the investment in resilience is enough, too little, or potentially too much, for the system and ensemble of hazards being considered. Economic assessments underscore the significance of proactive adaptation to climate change. Understanding the economic impacts of climate change on infrastructure, such as roads and bridges, is vital for decision-making (Neumann *et al.*, 2015; Twerefou *et al.*, 2015). Quantitative vulnerability assessments and adaptation options are crucial for constructing a more resilient transportation network (Schweikert *et al.*, 2015).

It has been in practice for decades using standard Cost-Benefit Analysis (CBA) or Cost-Effectiveness Analysis (CEA) for evaluating the tradeoffs between infrastructure investment and key objectives central to the decisionmaking (Cervigni *et al.*, 2015; Melvin *et al.*, 2016; National Academies of Sciences, Engineering & Medicine, 2021; Neumann *et al.*, 2015). While a CEA calculates the cost per unit of effect, a CBA calculates the ratio of all costs to all benefits of a program. The methodology encompasses several key steps. Initially, it involves identifying all costs and benefits associated with the investment, including any avoided costs that result from increased resilience, such as the avoided costs by investing in climate adaptation (Neumann *et al.*, 2021). Next, these identified costs and benefits are monetized; however, in the case of CEA, benefits are retained as indicators. CBA involves assigning a monetary value to each benefit, such as time savings, safety, noise, air pollution, and greenhouse gas (GHG) emissions. Subsequently, discounting is applied to future costs and benefits to calculate their present value. Sensitivity analysis is then conducted to test the robustness of the CBA results against changes in key assumptions. Finally, decision criteria such as the Net Present Value (NPV) or Benefit-Cost Ratio (BCR) are used to assess the project's feasibility or to compare different alternatives (Drupp *et al.*, 2024). These steps are formalized within a CBA framework to ensure a systematic evaluation of the trade-offs between different investment options and the performance of key outcomes.

2.2 Strategic Financial Planning for Long-Term Resilience

Current market valuations do not fully incorporate future risks from extreme weather patterns and supply-chain disruptions of the energy systems, including the repercussions of stranded assets and the extensive, often unquantified, co-benefits of resilient infrastructure investments (Eriksson & Eriksson, 2022; Hallegatte, 2016; Itoh, 2018; Johansson & Hassel, 2010; Karlsson *et al.*, 2020). The crux of financing a resilient infrastructure lies in converting the associated benefits into tangible returns on investment that are easily discernible and valued by capital markets amidst emerging risks (Meyer & Schwarze, 2019; Neumann *et al.*, 2021). Financing infrastructure is a complex challenge, with private investments and public sectors constantly prioritizing short-term fiscal needs over the critical long-term investments necessary for a region's economic backbone.

Traditional infrastructure, designed to support a country's or city's fundamental facilities and systems, now faces the pressing need for resilience against the multifaceted impacts of climate change (Eriksson & Eriksson, 2022; Izaguirre *et al.*, 2021; Verschuur *et al.*, 2024). This new breed of infrastructure must withstand and rapidly recover from extreme weather events and adapt to gradual shifts like altered precipitation and temperature patterns. Beyond mere adaptation, infrastructure must evolve to meet local and global climate mitigation regulations that could significantly impact community well-being and economic vitality. Consequently, decision-making around infrastructure must pivot away from fossil fuel dependencies and towards a mix of sustainable technologies, regulatory frameworks, and demand-side management policies that encourage behavioral changes. The economic returns from investing in resilient infrastructure must be evaluated for immediate and longterm benefits. These returns encapsulate the value of adaptation investments and inform decision-making processes that support sustainability. Recently ISO 22301 (ISO, 2024), developed by the Swedish Civil Contingencies Agency in collaboration with ISO and the Swedish Institute for Standards, updates it Business Continuity Management Systems Requirements to further enhance the guidelines for valuing resilience. Integrating ISO 22301 into existing frameworks can provide organisations with structured methods for risk assessment, impact analysis, and continuity planning, ultimately contributing to organisational resilience.

The strategic focus on investments should bolster the resilience of the transportation system to withstand immediate disruptions and ensure long-term alignment with our climate action goals. Resilience in this context extends beyond maintaining service delivery amid adversity; it includes the adaptability of our infrastructure and the continuity of energy supply in a low-carbon fuel transportation landscape under changing climate conditions. The economic assessment tools must evolve to navigate the uncertainties of this transition, employing novel socio-economic modelling techniques that accurately reflect the costs, benefits, and risks associated with the expansion of future transportation infrastructure. While advancements in research have enriched our understanding of critical infrastructure resilience and recovery capabilities in the face of crises (Cervigni *et al.*, 2015; Melvin *et al.*, 2016; Neumann *et al.*, 2015), National Academies of Sciences, Engineering and Medicine (2021) and Verschuur *et al.* (2024) highlight various significant deficiencies in current research, pointing out the need for a modeling framework that integrates multihazard and multi-infrastructure interactions. They also note a lack of research on specific climate hazards and infrastructure types, challenges in extending climate risk analysis over different geographical areas, and the growing difficulty in model validation. Additionally, they suggest that there is room for increased cross-sectoral knowledge transfer, a need for incorporating equity into modeling approaches, and a call for broader quantification of impact metrics.

Modeling these interdependencies elucidates the complex relationships and vulnerabilities between systems, advocating for an integrated resilience enhancement approach (Hallegatte, 2016; Itoh, 2018). Furthermore, exploring the economic dimensions of infrastructure recovery post-disaster reveals strategic insights for resource allocation towards enhancing long-term sustainability and resilience (Itoh, 2018). In their holistic assessment, Amoaning-Yankson and Amekudzi-Kennedy (2017) merge ecological, social, and economic frameworks to dissect transportation system resilience. This amalgamation portrays resilience as a dynamic attribute requiring systems to be adaptable, inclusive, and economically sustainable, capable of responding to, recovering from, and evolving due to disruptions. This comprehensive understanding underscores a transportation system's need to be resilient not just in immediate disruptions but also flexible and robust, capable of adapting to long-term environmental and societal shifts.

There are three key elements to enhance the decision analysis framework for resilience assessment in future transportation systems: measuring resilience at the system level, identifying new risks associated with energy supply chains in transportation, and conducting rigorous scenario analysis for robust decisionmaking. Detailed elaborations on each of these areas follow.

2.3 Measuring Resilience Metrics at the System Level

Functionality metrics are critical in measuring the consequences of hazard events and the benefits of resilience interventions. In transportation literature, functionality metrics for resilience analysis are typically specific to the mode or service and the scale of the analysis (Cervigni *et al.*, 2015; Melvin *et al.*, 2016; Neumann *et al.*, 2015; Verschuur *et al.*, 2022; Verschuur, Koks, & Hall, 2023; Verschuur, Koks, Li, & Hall, 2023). Resilience impact metrics are essential for evaluating and strengthening the preparedness of critical infrastructure systems against a diverse range of hazards. These metrics serve multiple crucial roles: they measure infrastructure robustness, guide risk management efforts, establish resilience benchmarks, and facilitate economic analyses of resilience investments (Roege *et al.*, 2014). By quantifying how infrastructure can withstand and recover from disturbances, impact metrics highlight vulnerabilities and prioritize necessary enhancements. They enable detailed risk assessments by linking specific hazards to their potential impacts, which is crucial for strategic planning and resource allocation. Additionally, these metrics set performance standards to ensure infrastructure reliability under adverse conditions and support cost-benefit analyses that justify investments in resilience by comparing potential economic savings against the costs of implementation. In essence, resilience impact metrics provide a comprehensive framework for improving infrastructure resilience, guiding both policy and practical applications to ensure systems are not only prepared for current challenges but also adaptable to future demands.

Resilience analysis and planning methods vary by discipline and are also specific to stakeholders, mode or service, and scale of the analysis. Conventional functionality metrics, though already comprehensive, tend to focus on the availability or performance of separate transportation subsystems: passenger or freight, infrastructure or modes. Energy is largely treated as another isolated subsystem, and most of the energy metrics have been traditionally related to stored fuel volumes or prices, which can be indicators of impending shortages (**Table 1**).

Transitioning towards more holistic, system-oriented measurement metrics is crucial for enhancing resilience planning in infrastructure systems for two main reasons. Firstly, system-level metrics provide a strategic approach by revealing the interconnections between different sub-systems, such as transportation modes, and infrastructure systems, aiding in identifying critical nodes and links essential for overall system resilience (Balakrishnan & Zhang, 2020). These metrics offer a comprehensive view of infrastructure vulnerability to multi-hazard scenarios and illustrate how disruptions in one part of the network can lead to cascading failures, intensifying the initial impact (Pagani *et al.*, 2019).

Secondly, as transportation, energy, and communication networks evolve, the impacts of new risks from emerging technologies, climate change, and alternative fuels have not been thoroughly assessed across system boundaries (Balakrishnan & Zhang, 2020; Verschuur *et al.*, 2024). System-oriented measurement metrics are essential not only for safeguarding physical assets but also for ensuring service continuity, crucial for economic stability and public safety during unpredictable disasters (Kong *et al.*, 2018). By utilizing these metrics to prioritize investments in high-risk nodes and pathways, stakeholders can proactively mitigate potential failures and enhance overall system resilience.

Addressing the resilience of future transportation systems may benefit from their closer integration with power systems, in which resilience and robustness have always been critical elements for decision making, due to the need to balance instantly supply with demand in the face of uncertain events and without the (easy) possibility of storing electricity. Dif ferent regulations and methodologies exist that require power system operators to account for potential, epistemic or non-epistemic, risks when designing or planning for resilient electricity generation or transmission systems (e.g. margin of reserve requirements, contingency N-1 static security assessments, Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE),

Table 1. System-level as well as mode- or service-oriented metrics for measuring the impacts of disruptions in transportation.

System	Mode	Impacts metrics
Overall		• Reliability – connectivity reliability; travel time reliability; capacity reliability; vulnerability index; expected fraction of travel demand post-disaster • Robustness and redundancy – node and edge failures; node survivability; robustness and fault tolerance; critical asset redundancy; connectivity loss; availability of alternative route • Recovery and response – restoration time; recovery budget; response and recovery capability; adaptability and resourcefulness
Passenger	IT & communication	• Systems/maintenance facilities downtime
	Roadways	• Link capacity; delay (travel time); safety; connectivity loss; availability of alternative route
	Intermodal transit terminals	• Node level connectivity; number of modes operating; terminal open/closed throughput
	Walking, bicycling, car	• Accessibility
	Regional passenger rail	• Signal systems downtime; absorption (passenger waiting time beyond a certain threshold); adaptation (represents starting of temporary train services on some part of the affected railway line to serve passengers); recovery (time to recover the damage condition of the impacted railway station and gain back the pre-disaster performance level)
	Bus, heavy-, light-, and commuter-rail, last-mile transit	• Time delays; travel time; idle time
	Air transport	• Maximum flow rate (number of takeoffs and landings); number of travellers served
Freight	Rail	• Track serviceability; Signal systems downtime; Terminals service time
	Air freight	• Maximum flow rate (number of takeoffs and landings); number of affected fleet size
	Port	• Ground access travel time; gantry crane efficiency; wharf productivity; electronic data interchange (EDI) connectivity; labour productivity; free trade zone (FTZ) business volume; total system restoration; time to full system service; time to α% resilience; inoperability and economic loss; network loss efficiency
Fossil Fuels	Natural gas & oil	• Response to demand fluctuations; physical shortage; price/Price volatility • Natural gas strategic reserve; petroleum strategic reserve
	Pipeline	• System level flow rate; storage facilities capacity and downtime

etc); and also for ensuring a fast recovery after an incident (such as primary or secondary reserve requirements)(Rodriguez-Matas *et al.*, 2024).

In the next section, we discuss the new risks associated with emerging energy supply chains in transportation, while risks related to climate change and new transportation technologies are discussed in other works.

2.4 Identifying New Risks Associated with New Energy Supply Chains

In the transition to non-fossil fuel transportation systems, a comprehensive understanding of associated risks is critical(Caputo *et al.*, 2011; Markert *et al.*, 2017). These risks generally fall into several categories: *Supply risks:* challenges such as low availability and high prices of alternative fuels; *Transitional risks:* issues arising from policy changes and the immaturity of new technologies; *Sustainability risks:* Environmental concerns, including high greenhouse gas emissions from certain bio-based or synthetic fuels; and *Safety risks:* dangers related to the handling, storage, and transportation of new fuel types.

Table 2 categorizes these risks into vulnerability and criticality aspects for various non-fossil fuel energy pathways. In resilience planning, these two concepts are often used together to identify where investment and intervention will be most effective. For instance, an asset that is both highly critical (due to its economic role or usage intensity) and highly vulnerable (due to its location or poor condition) would be a top priority for resilience measures. This intersection is typically represented through a prioritization matrix (National Academies of Sciences, Engineering & Medicine, 2021), allowing planners to systematically assess and address the most pressing needs.

As a hydrogen carrier and potential fuel, ammonia's (NH_3) vulnerabilities largely stem from its production dependency on green hydrogen and the nascent state of catalyst technologies. Its criticality includes the adaptation of existing infrastructures and engines to use ammonia safely due to its toxic properties (Chorowski & Krewer, 2023; Frankl & Krewer, 2020; Valera-Medina *et al.*, 2021). Methanol (CH_3OH) can be produced from biomass or by capturing and converting CO_2, methanol's vulnerabilities are tied to the availability and sustainability of its source materials and the efficiency of its production process. Its criticality factors include the ability to scale up production and distribution networks effectively and its emission profiles when used as a fuel compared to traditional hydrocarbon fuels (González-Garay & Smith, 2022).

Non-fossil fuels like electricity, hydrogen, e-fuels, ammonia, and methanol face common risks inherently linked to electricity networks, such as system integration challenges, peak load demands, grid disruptions, and price volatility. This interconnectedness can create cascading, consecutive, or concurrent hazard impacts where a disruption in one infrastructure service precipitates disturbances across multiple sectors, or from one transportation mode to other transportation modes (Verschuur *et al.*, 2024). Understanding and mitigating these complex interdependencies can only be done through scenario analyses and decision tools that capture the ripple effects across interconnected infrastructure systems and the broader economic landscape they support.

Table 2. Potential risks of non-fossil transportation fuels

Energy Pathway	Vulnerability	Criticality
Cross-cutting	Electricity-based fuels: • System integration challenges • Response to peak load demands • Resilience to grid disruptions • Intermodal connectivity • Sensitivity to electricity price volatility	• Response to rapid technology shifts • Decarbonization impact • Emission reduction effectiveness • Critical infrastructure dependencies • Robustness of supply chains • Adaptability to policy changes
Electricity (EVs)	• Availability of chargers in extreme weather conditions • Dependence on rare earth materials for batteries	• Infrastructure scalability • Battery disposal and recycling challenges
Bio-based fuels	• Impact of climate variability on feedstock • Water usage and land use conflicts	• Lifecycle greenhouse gas emissions • Feedstock sourcing ethics
Hydrogen	• High costs of infrastructure development • Dependence on low-cost renewable electricity • Safety concerns related to storage and transportation	• Scalability of production facilities • Resilience of distribution networks • Economic viability of hydrogen supply chains
E-fuels	• High cost of production • Fluctuations in biomass (if used as feedstock) or CO_2 capture sources	• Stability of synthetic fuel supply chains
Ammonia	• Dependency on green hydrogen availability	• Toxicity and safety measures in storage and transport
Methanol	• Fluctuations in biomass (if used as a feedstock) or CO_2 capture sources	• Scalability of production and distribution networks • Emission profiles compared to conventional fuels

2.5 Conducting Rigorous Scenario Analysis for Robust Decisionmaking

Scenario analysis not only demands a careful consideration of uncertainties and the development of consistent scenarios but also often requires complex interpretation of results. Addressing epistemic uncertainty, robust optimization has emerged as a favored approach in many disciplines to ensure that system constraints are reliably met. Rodriguez-Matas *et al.* (2024) have recently introduced an algorithm that integrates robust optimization into the constraints while applying the Savage criterion for decision-making under uncertainty within the objective function. This innovative approach helps in constructing scenarios that are not only resilient but also adaptable to varying conditions and unforeseen disruptions.

A range of models can be employed to explore the complex interdependencies within infrastructure systems (Balakrishnan & Zhang, 2020). A central tool is the Infrastructure Interdependency Model (IIM), which uses the economic input-output model to assess the impacts of failures across interconnected networks. This model, established by Y. Haimes and Jiang (2001), has been advanced into dynamic and fuzzy dynamic versions to account for changes over time (Y. Y. Haimes *et al.*, 2005; Oliva *et al.*, 2011). Other models complement the IIM, such as empirical models that analyze historical data to determine failure frequencies and interdependencies (Luiijf *et al.*, 2009; Mendon¸ca & Wallace, 2006), system dynamics-based models that apply nonlinear dynamics for resource and information flows (Pasqualini & Witkowski, 2005; Powell *et al.*, 2008; Santella *et al.*, 2009), economic theory-based models that expand on traditional input-output approaches (Y. Haimes & Jiang, 2001; Y. Y. Haimes *et al.*, 2005), network-based models using graph theory to depict systems (Dunn *et al.*, 2013; Svendsen & Wolthusen, 2007), and agent-based models simulating agent interactions under specific rules for complex decision-making (Balakrishnan & Zhang, 2020; Nilsson & Darley, 2006; Oliva *et al.*, 2010; Tesfatsion, 2003). These methodologies enable a thorough assessment of system vulnerabilities and support resilience enhancement against multiple hazards.

3. Responsibility of Stakeholders

The delineation of responsibilities for risk management within the transportation energy system requires an understanding of the system's multi-sector dynamics and the roles of the stakeholders in each (Willis & Loa, 2020). As the transportation energy system evolves in response to climate change, incorporating more fuels and supply chains, the landscape of risks and the corresponding responsibilities broaden and deepen. This system is characterized by a complex web of stakeholders, each playing a role in managing systemic risks. The interconnectedness of the systems implies that disruptions can cascade through supply chains and economies, necessitating a shared responsibility

Table 3. Stakeholders' responsibilities in enhancing resilience in sustainable transportation systems

Stakeholder	Role Responsibility	Causal Responsibility	Liability	Capacity for Action
Energy Providers	Supply energy sustainably and reliably	Minimize carbon footprint	Address production and operational risks	Invest in renewable energy technologies
Infrastructure Developers	Develop and maintain resilient transportation infrastructure	Ensure sustainable construction practices	Safety and compliance in construction	Innovate in climate-adaptive infrastructure design
Transport Service Providers	Offer eco-friendly transport services	Adopt and promote low-emission vehicles	Ensure safety and reliability of transport services	Lead initiatives for green transport solutions
Policymakers	Formulate and enforce sustainable transport policies	Drive environmental regulation compliance	Legal oversight and policy enforcement	Facilitate policy changes for climate resilience
Urban Planners	Design efficient and sustainable urban transport systems	Influence urban layout to reduce emissions	Ensure planning adheres to safety and sustainability standards	Integrate climate resilience into urban planning
Financial Institutions	Fund sustainable transport and infrastructure projects	Support investments in low-carbon technologies	Manage financial risks associated with green investments	Enable transition financing for sustainable projects
Community Leaders & Local Governments	Lead local sustainability and transport initiatives	Advocate for and implement local climate actions	Ensure regulatory and policy compliance at the local level	Enhance community engagement and resilience initiatives
Consumers	Choose sustainable transport options	Reduce personal transport emissions	Maintain responsible use of transport services	Advocate and support sustainable transport practices

approach, with roles clearly defined through public-private partnerships and stakeholder engagement (Nguyen *et al.*, 2022). Preparedness for both expected and unexpected risks is essential, calling for adaptive management and flexible planning to address the unpredictability associated with future risks. This approach ensures the system's ability to withstand sudden shocks and facilitate both immediate recovery and long-term adaptation strategies (Esfahani *et al.*, 2021; Sovacool & Mukherjee, 2011).

To clarify the roles and responsibilities of stakeholders in risk management, **Table 3** provides a structured overview. The table organizes stakeholders according to four key dimensions (Fahlquist, 2009; van de Poel & Fahlquist, 2012). (1) Role Responsibility: This refers to the primary functions or actions that stakeholders directly undertake within the transportation system. It encompasses the core activities for which each stakeholder is primarily known or involved. For instance, energy providers' role is to supply energy sustainably and reliably. (2) Causal Responsibility: This dimension focuses on the stakeholders' responsibility for addressing the causes or mitigating the effects related to system risks. It involves proactive measures to prevent or minimize risk impacts. For example, transportation service providers adopting low-emission vehicles and fuels directly address environmental concerns. (3) Liability: Liability refers to the legal and ethical responsibility stakeholders have in the case of accidents, failures, or non-compliance with regulations. This category outlines who is held accountable when things go wrong. Infrastructure developers, for instance, manage construction safety, ensuring adherence to safety standards. And last but not least, (4) Capacity for Action: This captures the stakeholders' ability to influence or enact changes within the system, often through innovation, policy, or research. It extends beyond their immediate role to include actions contributing to systemic resilience and sustainability. The capacity of energy providers to invest in renewable technologies exemplifies this, indicating a strategic capability to transform the energy landscape for transportation. By delineating these categories, we gain a clearer understanding of the multifaceted roles stakeholders play in managing and mitigating risks within the transportation system. Each category represents a distinct aspect of stakeholder involvement, from their direct actions (Role) to their broader capabilities to effect change (Capacity). This structured approach aids in comprehensively analyzing and assigning responsibilities, ensuring a cohesive strategy for risk management and sustainable system development.

4. Conclusions

The shift towards a low-carbon future in the transportation sector necessitates a comprehensive reevaluation of resilience metrics to better manage the unique challenges and complexities of decentralized energy systems. Infrastructure investments need to be assessed recognizing that climate and the risk of extreme events are changing. The effects of climate-induced extreme events are likely to be important, but are incompletely understood and remain an emerging area for research. This paper identifies the shortcomings of traditional resilience metrics that are rooted in centralized fossil fuel paradigms and advocates for the development of new system-level metrics under the MSD framework. These metrics are intended to address the multifaceted risks associated with various low-carbon energy pathways and their implications for the transportation sector. The proposed approach not only enhances understanding of system interdependencies but also encourages robust planning and adaptive strategies to mitigate risks in a transitioning energy landscape. By leveraging insights from various disciplines and employing advanced modeling tools, this research supports the development of resilient transportation systems equipped to navigate the uncertainties of a low-carbon future. Future efforts should focus on refining these metrics and integrating them into practical decision-making processes to support sustainable and resilient transportation infrastructure development.

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