BUILDING RESILIENCE IN DECARBONIZED TRANSPORT SYSTEMS: A MULTI-SYSTEM APPROACH

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Overview

Transportation systems worldwide are undergoing a rapid and radical transformation while facing new challenges brought on by environmental and technological change. The transition to low- and zero-emission transportation technologies introduces complex challenges that traditional resilience metrics fail to address. Emerging stressors—including climate change, pandemics, and technological advancements like autonomous vehicles and artificial intelligence—expose vulnerabilities in current transportation systems. The integration of alternative fuels such as electricity, hydrogen, e-fuels, ammonia, and methanol further complicates resilience planning due to their unique supply chains and infrastructure requirements. These developments necessitate a reevaluation and possible expansion of resilience metrics taking a comprehensive, system-oriented approach to resilience that accounts for the interdependencies among transportation, energy, and communication networks. We advocate for the adoption of multi-system dynamics (MSD) as a framework to enhance resilience in decarbonized transportation systems. MSD emphasizes the interconnectedness of various sectors and the need for holistic, system-level resilience metrics that considers how social systems interact with and respond to changes in infrastructure and the environment. By integrating scenario analysis and robust decision-making into strategic planning, stakeholders can better anticipate and mitigate cascading effects resulting from disruptions in one part of the system. The article underscores the importance of developing adaptive infrastructure and policies that can accommodate the uncertainties inherent in a low-carbon future where technology and the environment are changing, thereby fostering a sustainable and resilient transportation ecosystem.

Methods

MSD takes the perspective of a "system of systems," emphasizing that the transportation sector includes many sub-systems, including different modes, specific infrastructure components (e.g., highways, airports, ports), individual vehicles, various types of energy supply and demand, and energy production and distribution infrastructure. The purpose of the transportation system is to move people and goods to their destinations. Vehicle flows—automobiles, trucks, trains, ships, airplanes, etc.—comprise the operational dynamics, where the choice of mode influences the pattern and volume of vehicle flows. Vehicle movements are supported by a largely fixed physical infrastructure system—tangible assets like roadways, rail tracks, ports, and airports—and sometimes intangible support systems necessary for their operation and maintenance. 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, requiring a multi-system dynamics approach to understand the transportation sector (Fig 1).

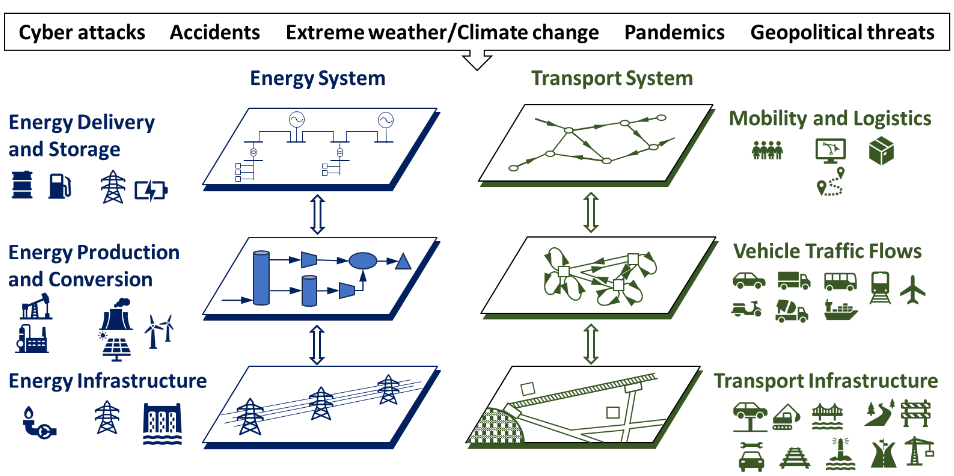

Figure 1: Integrated framework of the transportation system within a multi-system dynamics (MSD) Perspective. This schematic illustrates transportation as a system composed of various subsystems: mobility and logistics, vehicles, and transportation infrastructure (in green), and the energy system (in blue), including energy delivery, storage, production and conversion, and infrastructure. The top bar illustrates emerging stressors impacting the transport system, such as climate change, digital disruptions, and supply chain shocks. MSD takes a "system of systems" approach that recognizes the interdependencies between transport, energy, digital infrastructure, and socio-economic factors, offering a comprehensive framework that enables resilience planning across these interconnected systems. Figure inspired by Wandel et al.

Results

Along with substantial societal benefits, the transition to non-fossil fuel transportation systems also introduces several associated risks. 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. In light of these categories, Table 2 presents a detailed overview of how different fuel pathways—such as electricity, hydrogen, biofuels, e-fuels, ammonia, and methanol—exhibit varying degrees of vulnerability across these resilience factors. This table is designed to help readers grasp the different aspects of resilience that should be considered when planning for future transportation systems and the energy supply that supports them.

Table 2: Resilience Factors Across Different Energy Pathways for Transportation. *Low* indicates that the pathway currently faces significant challenges or barriers. *Medium* suggests a moderate performance, with some risks or opportunities for improvement. *High* represents favorable conditions that contribute positively to resilience across the given dimension.

Energy Pathway	**Supply Chain Robustness**	**Operational Reliability**	**Environmental Impact**	**Safety Management**
Electricity (EVs)	*Medium*: Dependent on critical materials (e.g., lithium, cobalt). Vulnerable to supply chain disruptions.	*High*: Well-developed charging infrastructure in many regions, but reliability is impacted by grid stability and extreme weather.	*Mixed*: Battery production has high carbon footprint, but overall lifecycle emissions are lower than fossil fuels.	*Medium*: Battery fires pose risks, particularly in accidents. Need for advancements in thermal management.
Hydrogen	*Low*: Production depends on green electricity. Supply chain not well-established. High transport and storage complexity.	*Medium*: Emerging infrastructure, reliant on high renewable energy availability. Prone to operational interruptions.	*High*: Clean if produced using renewable energy. Minimal emissions if effectively integrated.	*Low*: Safety concerns due to explosiveness. Specialized transport and storage requirements are costly and complex.
Biofuels	*Medium*: Vulnerable to climate impacts on feedstock supply. Competes with food production, creating possible shortages.	*High*: Can use existing infrastructure for transport and refueling, which enhances reliability.	*Low to Medium*: Significant environmental impacts due to land use changes and emissions during cultivation and processing.	*Medium*: Similar risks to conventional fuels, including flammability and local air pollution concerns.
E-fuels	*Low*: Dependent on CO_2 capture and renewable energy for production. Current supply is limited and costly.	*Medium*: Emerging infrastructure; dependent on market support and production efficiency improvements.	*Medium*: Lifecycle emissions depend on electricity source used for production. Lower GHG potential compared to fossil fuels.	*Medium*: Flammability and storage pose risks, similar to conventional liquid fuels.
Ammonia	*Low*: Dependent on green hydrogen, which links it to dual supply chain vulnerabilities. Production costs are high.	*Low to Medium*: Infrastructure is underdeveloped. Challenges in transport due to its toxicity.	*Medium*: Emissions during production can be managed, but concerns about nitrogen oxides persist.	*Low*: High toxicity requires stringent safety measures for handling, storage, and transport.
Methanol	*Medium*: Availability depends on CO_2 or biomass feedstock. Competing demands for feedstock can affect stability.	*Medium*: Similar operational characteristics to gasoline, which provides some reliability in existing systems.	*Medium*: Impact depends on feedstock source; can have a high carbon footprint if produced using non-renewable sources.	*Medium*: Corrosive properties require specialized handling and materials. High flammability.

Conclusions

The shift towards a low-carbon future in the transportation sector necessitates a comprehensive reevaluation of how we assess and prepare for resilience. Infrastructure investments must be made with an understanding that climate and the risk of extreme events are changing. The effects of climate-induced extreme events are likely to be significant but are incompletely understood and remain an emerging area for research. This paper highlights the limitations of traditional resilience metrics rooted in centralized fossil fuel paradigms and emphasizes the need for a holistic, system-level approach under the MSD framework. This approach addresses the multifaceted risks of various low-carbon energy pathways and their implications for the transportation sector. We can better mitigate risks in a transitioning energy landscape by enhancing our understanding of system interdependencies and encouraging robust planning and adaptive strategies. 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 integrating these holistic approaches into practical decision-making processes to support sustainable and resilient transportation infrastructure development. Future research should focus on developing region-specific and system-specific weighting frameworks for resilience metrics. Such methodologies would enable stakeholders to better tailor resilience assessments to local priorities, improving the applicability and impact of resilience strategies.

References

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