Resilient Mobility Under Multiple Shocks: The SCUDO Project Experience

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Abstract. The transport sector is increasingly exposed to disruptive events such as pandemics, natural hazards, cyber-attacks, and energy crises, which undermine both its reliability and its contribution to social equity. Traditional approaches have largely focused on protecting physical infrastructure, while more recent understandings of resilience emphasize the interdependence of technical performance, governance capacity, and users' socio-economic conditions. This paper develops an integrated framework of Key Performance Indicators (KPIs) that connects system-level resilience with socio-economic vulnerability to assess how different population groups anticipate, absorb, and recover from transport disruptions. The methodology combines a structured literature review with indicator design across six dimensions: robustness of infrastructure, operational continuity, governance and institutions, socio-economic accessibility, environmental sustainability, and systemic coherence. The framework is stress-tested on three types of disruption: pandemic, flood-related natural disasters, and energy price shocks-drawing on EU-level data and previous empirical studies to link performance metrics with profiles of vulnerable users. Results highlight that low-income, carless or car-dependent commuters, digitally excluded workers, and residents of isolated rural areas experience disproportionate exposure to service interruptions and energy price volatility, and benefit least from adaptive mechanisms such as telework, multimodal alternatives, and digital decision support. The paper argues that embedding equity-sensitive, resilience-oriented KPIs in transport planning and evaluation can support more robust, inclusive, and climate-resilient mobility policies across Europe.

Keywords: Transport disruption · Transport vulnerability · Key Performance Indicators · Natural disasters

1 Introduction

In recent years, transport systems have faced mounting disruptions from pandemics, extreme weather events, cyber incidents, and energy-related shocks, challenging both operational reliability and the sector's contribution to social equity [1]. These shocks

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increasingly interact with long-term pressures such as climate change, demographic ageing and digitalization, creating complex risk profiles that cannot be adequately understood through purely engineering-based approaches [2]. At the same time, decarbonization pathways and the electrification of transport infrastructures introduce new dependencies on energy and digital systems, which may themselves become sources of vulnerability under disruption [1]. Traditional resilience strategies have typically prioritized the protection and rapid restoration of physical infrastructure, emphasising standards, design codes and asset management practices aimed at reducing direct damage and shortening repair times. While these perspectives remain essential, they often treat users as homogeneous and pay limited attention to how different social groups experience and respond to disruptions in terms of accessibility, affordability and travel opportunities. In addition, most existing indicator frameworks assess single hazards or focus on network-level performance, with limited capacity to capture cascading effects across systems and distributional consequences for vulnerable groups. Recent approaches argue that resilience should instead be conceptualized as a socio-technical property, emerging from interactions between infrastructure robustness, operational strategies, institutional capacities, and the resources and constraints that shape user behavior [2]. In this perspective, there is a growing need for integrated indicator sets that link these interacting dimensions to concrete disruption archetypes and vulnerability profiles, in a way that is operational for planning and evaluation. Building on early evidence and methodological work developed within the SCUDO (Safe and Comprehensive Urban Development and Transport management for Disruption-resilient Operations) project, this paper proposes an integrated KPI (Key Performance Indicators) framework that explicitly connects disruption types, system responses, and vulnerability profiles across different territorial contexts. The framework responds to calls in the literature for metrics that can support scenario-based assessment of resilience measures while avoiding "average-only" evaluations that obscure distributional effects. It does so by combining quantitative indicators of network performance and recovery with qualitative indicators of governance, institutional coordination and user experience, structured in a way that allows decision-makers to trace how shocks propagate through systems of infrastructure, services and social practices.

2 Conceptual Framework

A growing body of literature conceptualizes resilience as a combination of outcomes (such as continuity of service and time-to-recovery) and capabilities (such as preparedness, coordination, adaptability, and learning) [3, 4]. Outcome-oriented indicators typically measure how much service is maintained during a disruption, how quickly performance is restored, and how severe the residual impacts are for users and operators [5]. Capability-oriented indicators, by contrast, focus on the institutional and organizational arrangements that enable systems to anticipate shocks, absorb disturbances, reorganize operations and incorporate lessons into future planning cycles [4]. Bringing these two perspectives together allows transport authorities to evaluate not only whether systems "bounce back", but also whether they can adapt and transform in ways that reduce future exposure and vulnerability [6].

Evidence syntheses show that disruptions can generate cascading impacts on mobility and accessibility, with uneven consequences across socio-economic groups and places.

For instance, damage to critical links or power supply can propagate through public transport and logistics networks, affecting not only travel times but also access to employment, health care and essential goods, especially in territories with limited redundancy or weak multimodal integration [1, 2]. The literature further demonstrates that the same disruption can have markedly different implications in dense urban cores, peri-urban belts and sparsely populated rural regions, depending on baseline service provision, availability of alternatives and the spatial distribution of opportunities [2].

Low-income households, car-less users, older adults, people with disabilities, women and caregivers, migrant workers, and rural residents frequently face higher exposure to disruptions, fewer feasible alternatives, and slower recovery trajectories [1, 5]. These groups are often constrained by limited financial resources, job inflexibility, caring responsibilities, physical or sensory impairments, language barriers and restricted access to digital information, all of which reduce their capacity to reroute, reschedule or switch modes when regular services are disrupted [2, 4]. Non-teleworkable workers, for example, remain dependent on commuting during pandemics or fuel price spikes, while many rural residents have no viable alternatives to a small number of bus routes or road corridors when these are affected by floods or snowstorms. Recognizing these differentiated vulnerabilities is therefore central to any attempt to design resilience metrics that go beyond system averages and account for distributional outcomes.

Recent contributions emphasize that bridging human and infrastructure resilience requires metrics that capture both network performance and the social capacity to anticipate, absorb, and adapt to shocks [2]. This implies integrating insights from socio-ecological resilience theory, which highlights feedbacks between human behavior, institutions and physical systems, with more traditional reliability and risk assessment approaches used in transport engineering [3]. From this vantage point, resilience is not an inherent property of assets or technologies, but the emergent result of how they are planned, governed and used by diverse actors over time (Fig. 1) [4]. The KPI framework proposed in this paper builds on this understanding, seeking to move beyond “average-only” solutions toward equity-sensitive resilience appraisal that explicitly links disruption types, performance indicators, governance capacities and user vulnerabilities within a coherent analytical structure.

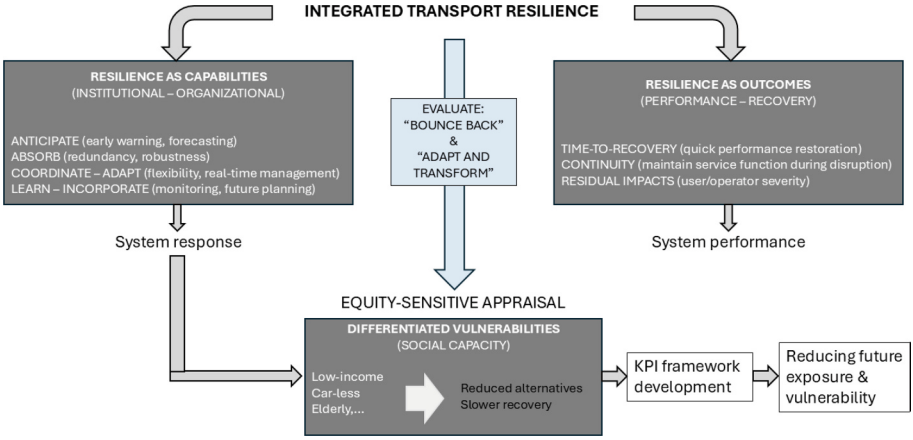

Fig. 1. Overview of the conceptual framework. Own elaboration.

3 Methodology

The methodology combines a structured review of peer-reviewed studies and EU reports—see Sect. 2—with the design of an operational indicator framework for resilience appraisal (Fig. 2).

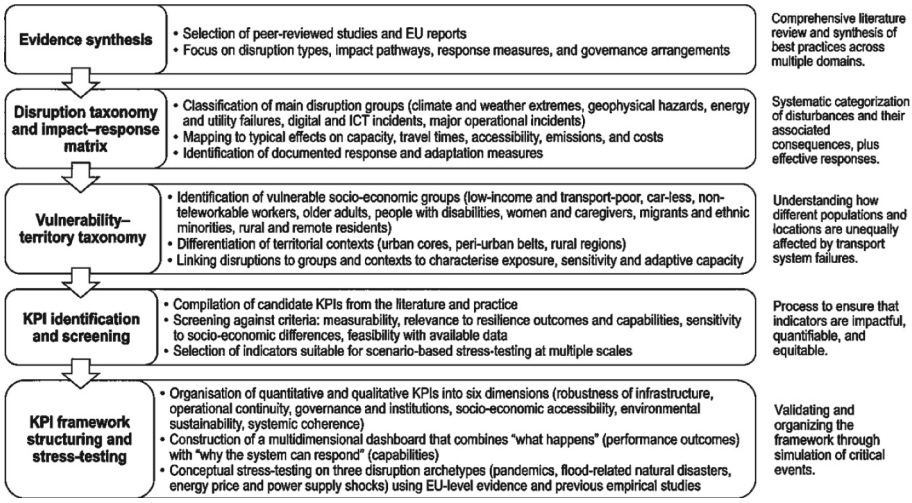

Fig. 2. Methodological framework (own elaboration)

The literature review is organized in three steps: first, it identifies key conceptual and empirical contributions on transport resilience, focusing on how disruptions affect both infrastructure performance and user experience. Second, it extracts information

on disruption types, impact pathways, and response measures, paying particular attention to the role of institutions, governance arrangements and recovery strategies. Third, it synthesizes this material into a set of attributes and indicators that can be used to characterize resilience outcomes and capabilities across different transport modes and territorial contexts.

The main groups of transport disruptions are classified, including climate and weather extremes (floods, storms, heatwaves, wildfires), geophysical hazards (earthquakes), energy and utility failures (power supply disruptions), digital and ICT incidents (cyber disruptions), and major operational incidents (accidents, infrastructure failures, bottlenecks). For each disruption type, the review traces impact pathways on mobility services and accessibility, along with response measures and governance arrangements documented in case studies, discussion papers and technical guidelines. This allows the construction of a disruption/impact/response matrix that links hazards to typical effects on capacity, travel times, accessibility, emissions and costs, as well as to common mitigation and adaptation strategies.

The material is then used to develop an integrated taxonomy that links disruptions to socio-economic groups and geographic contexts, enabling KPI selection and scenario design that capture both performance and distributional outcomes. The taxonomy distinguishes, for example, between dense urban corridors with multiple modes, peri-urban areas with car-dependent travel patterns, and rural regions with sparse services, and associates each configuration with specific profiles of vulnerability and adaptive capacity. On this basis, candidate KPIs are screened against criteria of measurability, relevance to resilience outcomes and capabilities, sensitivity to socio-economic differences, and feasibility of application with available or realistically collectable data.

The resulting framework organizes quantitative and qualitative indicators around six dimensions, building on Karagiannakis et al. [7]: robustness of infrastructure, operational continuity, governance and institutions, socio-economic accessibility, environmental sustainability, and systemic coherence. Quantitative KPIs capture aspects such as redundancy ratios, percentage of service delivered, delay and cancellation rates, energy recovery intensity and composite resilience indices. Meanwhile, qualitative KPIs characterize, among others, coordination structures, equity criteria, integration with decarbonization policies and the role of digitalization in supporting decision-making and communication. These performance indicators form the backbone of a dashboard that can be applied in stress-testing exercises, where different disruption scenarios are used to explore how changes in infrastructure, operations or governance affect both system-level performance and the conditions of vulnerable user groups across diverse territorial settings.

Beyond defining the indicator set, the methodology explicitly addresses the sensitivity and reliability of the proposed KPIs before full application to a specific local case. Sensitivity is supported, first, by grounding the disruption/impact/response matrix in empirical evidence on how different shocks affect capacity, travel times, accessibility, emissions and costs, and second, by selecting indicators that have demonstrated responsiveness under disruption conditions in previous studies, such as percentage of service delivered, delay and cancellation rates, and accessibility losses for specific user groups.

Reliability is strengthened through screening criteria that prioritise measurability, interpretability for decision-makers, and feasibility with EU-level and national data, while ensuring that indicators remain applicable across diverse network structures and territorial contexts. The KPI framework is thus conceived as a transferable template which reflects consolidated evidence on disruption mechanisms and vulnerability patterns in different transport systems and modes.

4 KPI Framework Design and Testing

The KPI framework (Table 1) assesses resilience through a dashboard that combines "what happens" (performance outcomes) with "why the system can respond" (capabilities) [8]. Robustness of infrastructure includes indicators on the structural resistance of assets, redundancy in critical links, and vulnerability of nodes and corridors to specific hazards such as flooding or earthquakes. Operational continuity comprises metrics on service availability, capacity utilization, speed of degradation under stress, and time-to-recovery of different modes and routes. Governance and institutional capacity is captured through indicators of preparedness (existence of contingency plans and early warning systems), coordination across agencies and operators, data and information-sharing practices, and stakeholder involvement in resilience planning. Socio-economic accessibility focuses on the ability of different population groups to reach essential activities under disruption conditions, through indicators of affordability, availability of alternatives, and adaptability of travel behavior. Environmental sustainability incorporates metrics related to emissions, energy efficiency, and potential trade-offs between short-term recovery measures and long-term decarbonization goals. Finally, systemic coherence examines alignment across infrastructure, operations, governance, and user needs, ensuring that measures designed to protect network performance do not inadvertently deepen inequalities or lock in unsustainable patterns. In combination with the disruption/impact/response matrix and the disruption-vulnerability taxonomy developed in Sect. 3, this framework therefore offers an ex-ante tested structure in which indicators are expected to react in a consistent and interpretable way under different disruption scenarios.

The framework is stress-tested on three disruption archetypes: pandemics, flood-related natural disasters, and energy price or supply shocks, drawing on EU-relevant evidence and previous empirical studies [1, 5, 11]. Pandemics alter demand patterns through mobility restrictions and telework adoption, while imposing capacity constraints and safety protocols on public transport, with unequal impacts on workers whose jobs cannot be performed remotely. Flood-related disasters damage infrastructure, disrupt operations, and reconfigure accessibility landscapes, especially in territories with limited redundancy and weak evacuation logistics. Energy price shocks and power supply disruptions affect operating costs, service frequency, and fare levels, with knock-on effects on affordability and mode choice, particularly for households with constrained budgets or high commuting dependence.

Across these scenarios, several socio-economic groups consistently exhibit higher levels of vulnerability. Low-income and transport-poor households are more exposed to affordability stress and possess fewer options to substitute disrupted services or

Table 1. The KPI framework

Dimension	Quantitative KPIs	Qualitative KPIs	Sources
Technical / Infrastructure	Redundancy ratio; MTTR; % capacity loss	Resilience standards/codes	[7, 9]
Operations / Service performance	% service delivered; delay/cancellation rate; rerouting speed	Operational flexibility; passenger information procedures	[3, 5]
Governance / Institutional capacity	Plan update frequency; resilience budget share; joint exercises	Coordination structures; stakeholder inclusion	[4, 10]
Users & Equity	Access to essential services; affordability stress; coverage of vulnerable groups	Equity criteria; perceived reliability; inclusive communication	[2, 5]
Environment / Sustainability	Net emissions avoided; recovery energy intensity	Integration with decarbonisation policies	[1, 6]
Systemic / Cross-cutting	Composite resilience index; stress-test score	SDG alignment; electrification/digitalisation role	[8, 11]

absorb fares and fuel increases. Car-less households depend strongly on public transport and often lack accessible alternative modes when services are reduced or rerouted. Elderly people and people with disabilities face heightened sensitivity to disruption and additional accessibility barriers during emergency responses or recovery works. Women and caregivers are constrained by complex trip-chaining and care responsibilities, which make even minor disruptions disproportionately burdensome. Migrants and ethnic minorities may encounter language and information barriers, as well as rigid job and housing constraints that reduce adaptive capacity. Non-teleworkable workers are highly dependent on commuting even under mobility restrictions, limiting their ability to benefit from digital-based mitigation strategies. Rural and remote residents suffer from lower baseline service availability and longer access distances, leaving them more exposed to both service interruptions and energy price volatility.

By mapping disruption types to vulnerable groups and territorial configurations, the KPI framework supports scenario-based assessments that reveal both technical and equity implications of resilience strategies. Multidimensional KPIs enable ex-ante comparison of measures across infrastructure reinforcement, operational reconfiguration, governance reforms, and user-oriented interventions, thereby reducing reliance on single-metric or average performance evaluations [6]. For example, indicators of socio-economic accessibility and affordability can be combined with service continuity metrics to identify where maintaining minimum service levels for specific groups may be more critical than optimizing overall network efficiency under shock conditions.

Similarly, governance indicators related to communication channels, participatory planning, and data inclusiveness help assess whether digital tools and decision-support systems are accessible to digitally excluded users. The framework thus connects resilience enhancement with the design of targeted support mechanisms, such as protected service corridors for key workers, subsidized fares for low-income commuters, or enhanced demand-responsive transport in underserved rural areas [1, 5].

5 Discussion and Conclusion

The analysis confirms that resilience-oriented KPIs must systematically account for how different population groups anticipate, absorb, and recover from disruptions, paying particular attention to those with limited financial resources, constrained modal choices, or restricted digital access. The results highlight that low-income user, car-less or car-dependent commuters, digitally excluded workers, and residents of isolated rural areas experience disproportionate exposure to service interruptions and energy price volatility, and often benefit least from adaptive mechanisms such as telework, multimodal alternatives, or real-time digital information. Equity-sensitive KPI dashboards can guide policymakers in interrogating trade-offs between short-term restoration of capacity and longer-term goals of climate resilience and social inclusion [4, 6]. Embedding such dashboards into planning and evaluation routines may also facilitate cross-sectoral coordination, aligning transport resilience strategies with social policy, energy transitions, and regional development objectives [1, 10].

In conclusion, this paper presented an integrated KPI framework that connects system-level resilience with socio-economic vulnerability, structured around six dimensions spanning infrastructure, operations, governance, accessibility, environment, and systemic coherence. Drawing on evidence that disruptions generate cascading and unequal impacts, the framework foregrounds the experience of vulnerable users and enables equity-sensitive scenario design and appraisal. The approach is rooted in methodological advances initiated within the SCUDO project but is conceived to be transferable across European contexts and adaptable to different types of disruption. By embedding equity-sensitive, resilience-oriented KPIs into transport planning and evaluation, policymakers can support more robust, inclusive, and climate-resilient mobility systems under conditions of growing uncertainty and multiple shocks. Future research should refine indicator sets with empirical data, test their performance in real-world decision processes, and further explore how institutional arrangements shape both resilience outcomes and the distribution of benefits across user groups.

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Disclosure of Interests The authors declare no competing interest.

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