Transportation Resilience as a System-of-Systems

Technical report

2026-08-19

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This work was funded by the Swedish Strategic Vehicle Research and Innovation program, FFI (Vinnova grant no. 2025-00860).

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Summary

Transportation systems are becoming increasingly complex and represent systems-of-systems (SoS) of many independent actors, including also energy and communication systems. At the same time, disruptions in transportation systems are multiplying as an effect of climate change and geopolitical factors. This leads to an increasing need for methods to analyze and strengthen resilience in SoS. This report presents the findings from a pre-study project aiming at understanding how SoS and resilience engineering can be applied to contemporary and future transportation systems.

To establish the state-of-the-art of SoS resilience in general, a systematic literature review was conducted. It showed that there are two different worldviews of relevance to resilience, namely specified resilience which assumes knowledge about the disturbances, and general resilience which does not assume such knowledge. The specified resilience view dominates the literature and also lends itself to typical engineering approaches, but lacks realism when it comes to availability of data.

Among the many different techniques that have been used for modeling SoS for resilience analysis, a layered graph representation stands out. It describes the SoS in four layers: macro-layer, capturing its capabilities; meso-layer, showing how constellations contribute to the capabilities; micro-layer, showing how individual actors interact; and spatial layer, which describes the physical environment. Typical approaches to measuring resilience in SoS are also based on such a hierarchical structure, where macro-level resilience is aggregated from lower-level performance indicators, and also aggregated temporally over the resilience phases of preparation, absorption, recovery, and adaptation. The literature suggests various methods for improving SoS resilience, by interventions at different hierarchical levels, by improving the SoS architecture, or by considering sociotechnical aspects.

Based on these findings from the SoS literature, the road transportation system was analyzed in workshops with experts. The generic model of a layered graph was used, identifying concrete entities in each of the layers as well as some of their interactions. This analysis did not only consider the core transportation capabilities, but also, e.g., actors related to building and maintaining the infrastructure, energy providers, digital service providers, and authorities.

Existing methods for analyzing the resilience of the transportation system were evaluated, with an emphasis on tools for traffic forecasting and infrastructure planning. These established tools have a value in assessing steady-state traffic flows, but to investigate the dynamics of a disruption, brute-force methods are needed where parameters are varied systematically.

To broaden the perspectives beyond the physical infrastructure and traffic flows, a broad set of further indicators were identified. The indicators were classified according to resilience phase, system layer, type, analysis method, required data, and to what types of disruptions they are relevant. Further, they were grouped into what parts of the SoS they relate to, such as transport infrastructure, operations, logistics, energy, digital connectivity, economic and environmental effects, etc.

Based on these investigations, a number of challenges and knowledge gaps were identified, including the need for methods to handle general resilience where possible disruptions are not known; to improve analysis methods; to take into account the perspectives and incentives of different stakeholders; sociotechnical aspects and the human ability to contribute to resilience; costs of resilience; management of resilience; and addressing complexity.

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1 Introduction

Transportation systems are becoming increasingly complex because of optimization aiming at reduced cost and faster deliveries. New technologies are supporting an increase in transportation efficiency through digitalization, automation, and artificial intelligence. This is combined with solutions to reduce the environmental impact, leading to increasing use of electric propulsion. Further, different transportation modalities provided by independent actors are being used. Therefore, transportation systems can no longer be treated separately but are becoming deeply integrated with energy and communication infrastructures as well as with service providers and supply chain solutions. This turns transportation into a complex sociotechnical *system-of-systems (SoS)*, where various independent entities collaborate to achieve things that they cannot do on their own. This integration provides benefits but also creates new risks and vulnerabilities.

Contextual factors such as climate change and geopolitics bring increasing uncertainties in transportation and logistics, but efficient methods to prepare and act are lacking. Due to severe disruptions in recent years, e.g., the Covid-19 pandemic, the Suez Canal blockage, and the war affecting the Strait of Hormuz, the awareness of *resilience* is increasing, and the lack of systematic methods and knowledge calls for significant research in these areas.

The purpose of the work presented in this report was to investigate transportation system resilience using an SoS approach. In the remainder of this introduction, a more detailed description is provided of the core concepts in SoS and resilience, and how they have been applied to transportation. Based on that, the project context and research questions are defined, and an overview of the rest of the report is provided.

1.1 Systems-of-systems

The SoS concept emerged in the 1990s, as a result of the increasing possibility of information exchange driven by advances in telecommunication and the massive expansion of the Internet. Initial SoS applications were primarily in defense and aerospace, such as network-based defense and coalition warfare. The concept has then spread to other sectors such as emergency response, transportation, energy, infrastructure, healthcare, and economical networks (see, e.g., Nielsen, 2015).

A seminal paper by Maier (1996) characterizes SoS as having *constituent systems (CS)* with operational and managerial independence. The SoS also has emergent behavior, evolutionary development, and a geographical distribution. A set of SoS archetypes has been proposed, called directed, acknowledged, collaborative, and virtual SoS (Maier, 1996; Dahmann & Baldwin, 2008). These are primarily based on the extent to which participants agree on objectives and the degree of centralized control, on a falling scale from directed to virtual. In the defense sector, directed or acknowledged SoS with strong centralized control are common, whereas in other sectors, it is common to find collaborative or even virtual SoS without central control and agreed objectives.

The commonly used characterizations primarily focus on the relation between the SoS as a whole and the CS that make up its parts. However, to depict a realistic SoS, more concepts are usually necessary. The SoS as a whole represents a macro-level perspective, and the CS a micro-level description, but there is also a meso-level which captures the relations between groups of CS (Axelsson, 2019). Such a group is referred to as a *constellation*, and it is dynamically formed by the CS to operationally deliver a required capability at a certain time and place, after which it dissolves.

In addition to the ordinary CS, which have a certain independence of the SoS that allows them to also carry out tasks outside the SoS context, there is often a need for supplementary elements that facilitate

the SoS operation. Such *mediators* do not have the same independence, but provide essential internal capabilities for, e.g., coordination, communication, and networking (Axelsson, 2024).

1.2 Resilience

The term resilience is used to describe the ability of a system to withstand and recover from disturbances and disruptions and continue to evolve. The term was popularized in ecology by Holling (1973) and has subsequently been adopted in other domains (Bhamra et al., 2011). An overview of the usage of the term and application examples is provided by Martin-Breen & Anderies (2011).

The field of resilience engineering evolved from risk and safety engineering. It emphasizes concepts from complex adaptive systems, such as emergence, and frames resilience as a control problem of an organization (Hollnagel et al., 2006; Righi et al., 2015).

It is common to model resilience as four phases (Bruneau et al., 2003; Jesse et al., 2024), as illustrated in Figure 1:

- *Preparation*: During normal operation, the system prepares itself for possible future disruptions.
- *Absorption*: When a disruption occurs, the system continues to operate but with reduced capability.
- *Recovery*: After the disruption is over, the system gradually restores its original capabilities.
- *Adaptation*: The system learns from the event and adapts to better handle future disruptions.

A disruption results in a loss of value, and the magnitude of this loss depends both on the level of capability degradation and on the duration of the absorption and recovery phases. Measures of resilience thus need to combine both effectiveness level and duration.

The term resilience is related to several other terms, such as reliability, robustness, and risk. Scholz et al. (2012) suggested to view risk as a combination of the likelihood and severity of a threat, which assumes knowledge about events and losses. Resilience, on the other hand, is in their view the situation where those characteristics are not known. The usage of the terms in the literature is however not entirely consistent, and many sources use the term resilience where the term risk would

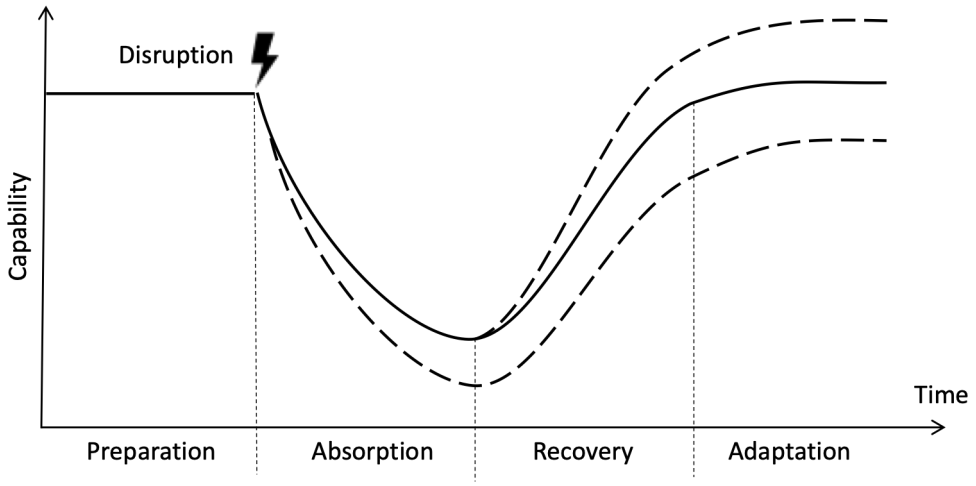

Figure 1. Resilience phases.

be more appropriate. In reality, both risk analysis and resilience are relevant topics simultaneously, and most complex SoS would contain some threats that are well-known, either based on the qualitative nature or sometimes even based on available statistical quantification of likelihood of occurrence. At the same time, other threats are not yet known, or even imaginable.

In this report, the term resilience is used broadly. When necessary, a distinction will be made between *specified and general resilience* (Cavallo, 2014; Cavallo & Ireland, 2014). Specified resilience treats disturbances whose characteristics are to some extent known and is thus close to risk analysis whereas general resilience does not assume this knowledge.

When addressing resilience, Wiig et al. (2020) points out four essential aspects that need to be considered:

- *Resilience for what*, which identifies what values are important to preserve;
- *Resilience of what*, referring to the elements that we seek to design to act resiliently;
- *Resilience to what*, addressing the challenges and uncertainties; and
- *Resilience through what*, i.e., the resources and activities that contribute to resilience.

1.3 Transportation resilience and SoS

Transportation resilience is a classical topic with established methods such as analysis of road vulnerability and connectivity (Berdica, 2002; Jenelius & Mattsson, 2021). The topic has been intensively researched lately, and several secondary studies exist. These include the resilience of specific supply chains, where systematic literature reviews exist (Ali et al., 2017; Kochan & Nowicki, 2018; Negri et al., 2021; Ribeiro & Barbosa-Povoa, 2018). Another well-surveyed area is the resilience of critical infrastructure, which also includes the transportation infrastructure (Mottahedi et al., 2021).

However, there is only a small number of research studies with the same focus as this report, namely, taking an SoS perspective on transportation resilience. In the road sector, the resilience of mobility as a service has been analyzed, with a focus on the IT aspects related to travel planning, ticketing, and payment (Zhang & Matsubara, 2025). The resilience of electrified goods transportation, with an emphasis on the transition from fossil fuels and the design of the energy supply system, has also been studied by Svenson et al. (2021). Mostafavi (2017) addresses the road infrastructure, identifying issues with financial planning when it comes to enhancing resilience.

1.4 Project context and research questions

This report documents the technical results of the pre-study project “Transportation Resilience as a System-of-Systems” (TReSoS1). The project was carried out in collaboration between Mälardalen University, TRATON, and WSP Sweden from August 2025 to July 2026. It was funded by the Swedish Strategic Vehicle Research and Innovation program, FFI (Vinnova grant no. 2025-00860.) The project aimed to investigate methods for SoS engineering to deal with resilience; transportation system resilience considering emerging technologies and trends; and the application of SoS methods to resilience engineering of transportation systems. The following overall research questions were defined:

1. What is the state-of-the-art of SoS engineering for resilience?
2. What are the existing methods to analyze and quantify transport system resilience and how can they further develop to address emerging challenges?
3. What research gaps are there regarding transport SoS resilience, and what research topics should be prioritized in the coming years for building long-term resilience?

The scope of the study was road transportation, but within a larger societal context which includes transportation in general and a broad range of stakeholders.

1.5 Report overview

The remainder of this report is structured as follows: In Chapter 2, the state-of-the-art of SoS resilience is reviewed, through a systematic literature study. In Chapter 3, this knowledge is applied to an analysis of the transportation system, based on expert workshops. Chapter 4 reviews some existing indicators of resilience in the road infrastructure, and the corresponding analysis methods. In Chapter 5, a catalogue of a broad range of potential indicators for transportation resilience is presented. Chapter 6 discusses some challenges and knowledge gaps identified in the study, and the final chapter concludes the report.

2 Systems-of-systems and resilience

Many SoS applications relate to critical capabilities and functions in society, that must be upheld also in the presence of disturbances. The question of resilience is hence very relevant to SoS, and there is a substantial body of research into SoS and resilience. However, the literature is scattered, and each study typically only considers a small subset of the relevant issues. Therefore, the project conducted a broad literature review on the subject of SoS resilience, thereby addressing the project's first overall research question: What is the state-of-the-art of SoS engineering for resilience?

This chapter contains a preliminary report of the literature review. The full details of the study will be the subject of a forthcoming article.

2.1 Method

The study described in this chapter follows a systematic literature review method (Kitchenham & Charters, 2007) aiming at answering the following detailed research questions:

1. What are the characteristics of the body of literature?
2. Which fundamental worldviews on resilience are represented?
3. How are SoS modeled to support resilience analysis and enhancement?
4. Which SoS resilience measures are proposed?
5. What SoS resilience enhancement approaches are proposed?

The literature was identified through searches in the Scopus database, using search strings combining the two terms "resilience" and "system-of-systems" (with different variants of spelling, etc.) in the title. The identified papers were screened, first based on title and abstract, and then on the full text. Papers that did not provide any insight into the study's research questions were excluded, as were papers not applicable to realistic SoS, not written in English, or for which the full text could not be retrieved. In the end, 63 papers were carried forward to further analysis.

To address each of the study's research questions, key elements of each paper's full text were extracted using a predefined protocol. The extracted data from all papers was put in a common table, allowing to summarize and compare individual aspects of the analysis across papers.

2.2 Literature characteristics

The first research question in the literature review concerned the characteristics of the body of literature on resilience of SoS, and this was addressed using a categorization of papers along different criteria and calculating and visualizing statistical data.

Figure 2 shows the number of publications per year, and for each year, it is also indicated how many papers there were from each region. The graph shows that there has been a continuous interest in the topic since 2009, with a slowly growing publication rate. What is also apparent is that the larger increase in recent years is a result of publications by Chinese authors, who now dominate the field.

Figure 3 shows the application areas addressed in different papers. The bars to the left show the total number of papers dealing with each area, whereas the connections to the right and bars at the top indicate how many papers addressed different combinations of applications. Often, a study with several applications addresses a particular aspect of SoS resilience and discusses how that applies in different domains. Usually, the applications are used as motivating examples rather than being based on concrete data from real-world SoS. The areas can be summarized as follows:

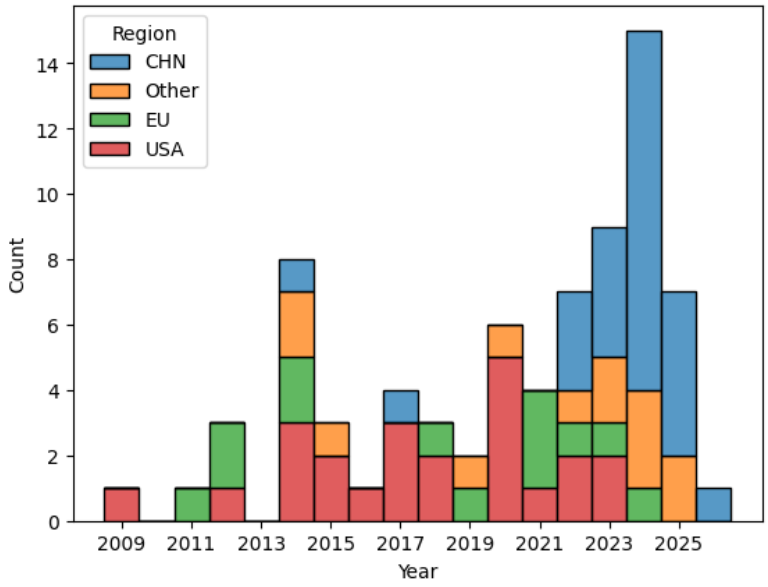

Figure 2. Number of primary studies per year and region (with partial data from 2025-26).

- *Defense*: The largest application area, with 25 papers addressing different branches of defense, including naval, air and space, land-based, joint operations, search-and-rescue, and unmanned systems. This category includes almost all the Chinese papers in the dataset.
- *Transportation*: The second largest area, with eleven papers discussing different modalities. This includes road transportation, mobility as a service, electrified goods transportation, road infrastructure, air traffic, and maritime goods transportation.
- *Energy*: Power production, transmission, storage, and control systems for electricity and gas.
- *Emergency response*: Earthquakes, floods, hurricanes, wildfires, disaster preparedness across societal actors, effects on infrastructure.
- *Economical networks and supply chains*: Industry value chains for industrial symbiosis, economic infrastructure for business ecosystems, forestry, and supply chains within manufacturing.
- *Social and societal*: Societal resilience and the interplay between health, environment, and economy of communities.
- *Unmanned aerial systems*: Multi-UAV systems, mostly related to defense applications.
- *Ecological*: Forestry and oyster reef ecosystems.

2.3 Resilience worldviews

The second research question in the literature review relates to the worldview on resilience reflected in the various papers. A worldview can be defined as a cognitive orientation of an individual towards a concept (Dori et al., 2020), i.e., a tendency to see the world in a certain way (Checkland & Poulter, 2006). For the resilience concept, two primary worldviews can be identified. The first takes an engineering perspective on resilience, trying to modify the system-of-interest from the outside. It assumes a well-defined system where at least some properties of the disturbances are known and the approach can thus deal with specified resilience. The other worldview takes a complex systems perspective and views resilience as being achieved from within the system-of-interest. It addresses general resilience where disturbances are not known.

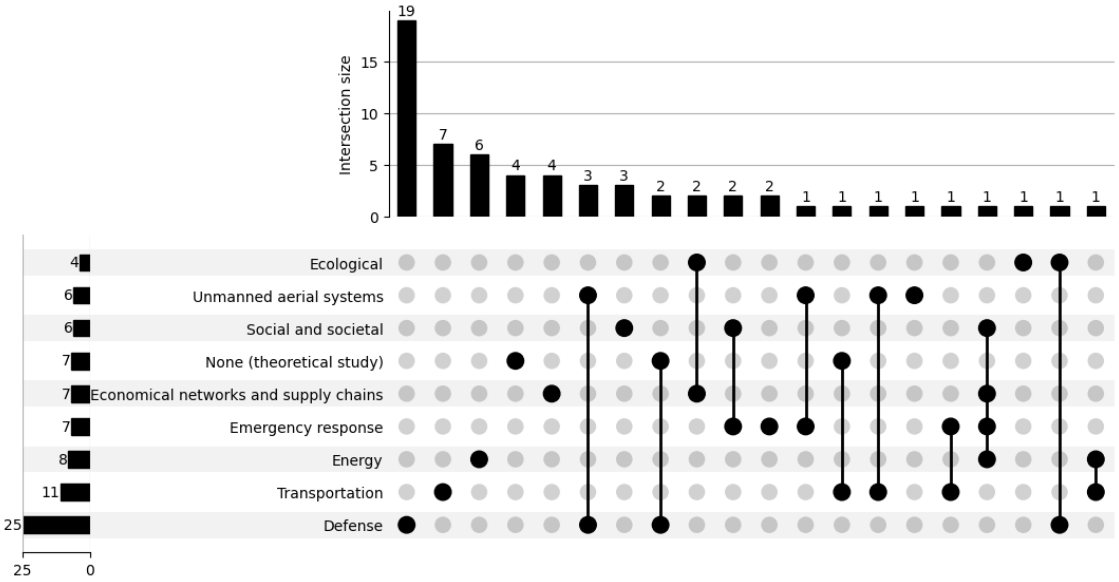

Figure 3. Number of primary studies per application area.

The vast majority of the primary studies can clearly be classified as following an engineering approach to resilience. According to Zhong et al. (2024), resilience research consists of three parts, namely model construction, resilience assessment, and resilience improvement. Expanding on this, Figure 4 shows a generic resilience engineering approach which most papers in the study aligns with, at least in part. The process starts with the recognition of a situation that can be viewed as an SoS and where resilience is important. Based on an analysis of the situation, an SoS model is constructed, on which all subsequent activities are based. By inspecting elements of the SoS models, risks can be identified which characterize the types of disturbances that can occur, in line with the specified resilience framing. By combining the structure of the SoS model and the disturbances in a causal analysis, measures of resilience are constructed which quantify the effects. These can then be used to explore a design space, expressed in terms of the SoS model, of resilience enhancement alternatives using an optimization approach.

The papers adopting an engineering worldview do usually not discuss this choice explicitly. In contrast, the much smaller group of papers that adopt the alternative worldview based on general resilience and complex systems motivate this choice in detail and discuss the key characteristics. Cavallo (2014) and Cavallo & Ireland (2014) introduced the dichotomy of specified and general resilience and elaborated on the differences. In their view, specified resilience with identified risks can be addressed using a reductionist approach based on deductive and inductive reasoning and linear thinking, where the identified risks can be monitored and mitigated. General resilience, dealing with unforeseen and interconnected risks, need to use systemic approaches, where systems thinking and abductive reasoning are essential. Systems thinking is needed to deal with emergent phenomena, since the consequences of interrelated events and cascading effects are not understood, even if all information is actually available. Abductive reasoning is to find the most plausible explanation to a given observation. This yields a hypothesis that can guide actions to validate or refute it, by probing the situation to learn more. Mitigation is then based on keeping the system within a safe operating space.

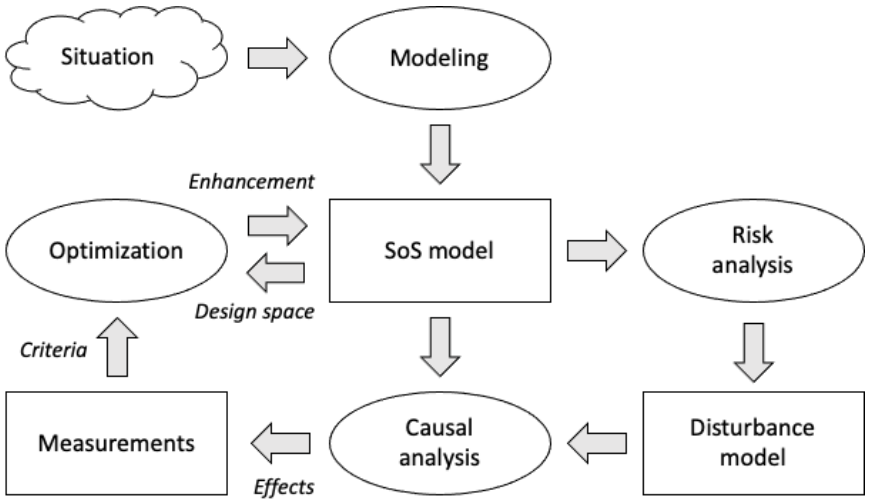

Figure 4. A generic SoS resilience engineering approach.

Based on this characterization of general resilience, Cavallo & Ireland (2014) propose a sensemaking framework based on complexity theory, building on, e.g., Cynefin (Snowden & Boone, 2007) and soft systems methodology (SSM) (Checkland & Poulter, 2006). The use of SSM, with its emphasis on comparing how different actors perceive a situation, aligns well with the SoS characteristic of independent CS, each with their own situation awareness. Others emphasize resilience as a continuous lifecycle process rather than a system property (Dreesbeimdiek et al., 2022).

2.4 SoS resilience modeling

The third research question of the literature review concerned how SoS can be modeled to support resilience analysis and enhancement. In the literature, three different approaches are presented. The first is based on systems engineering methods, such as architectural frameworks like DoDAF (Joannou et al., 2019) and UAF (Zhang et al., 2025), and systems modeling languages like SysML (Joannou et al., 2019), Archimate (Zhang et al., 2025), and UML. The aim is to capture essential characteristics of the SoS situation, to support communication and qualitative analysis in an engineering context.

The second direction uses systems thinking tools, such as Systemigrams (Mansouri et al., 2009), causal loop models (Joannou et al., 2019), and rich pictures (Joannou et al., 2019), to establish a qualitative description with a focus on identifying feedback loops. This can also be extended into quantitative system dynamics simulation models (Watson et al., 2022).

The third approach is based on the mathematical concept of graphs, consisting of nodes connected by edges. This is the most common technique in the literature on SoS and resilience, in particular within the extensive Chinese research on military applications. Often, the graph is divided into several layers, with different kinds of nodes. The layers are interrelated, where elements in a lower layer contribute to the emergence of properties at a higher layer, as illustrated in Figure 5. One possible division in layers is:

- *Macro*: Captures properties of the SoS as a whole, such as the capabilities it provides (Han et al., 2012; Jiao et al., 2024).
- *Meso*: Describes constellations, i.e., groups of CS collaborating to provide an SoS capability (Chen et al., 2024; Ning et al., 2024).
- *Micro*: Identifies individual CS and agents, and the communication paths between them (Jiao et al., 2024).

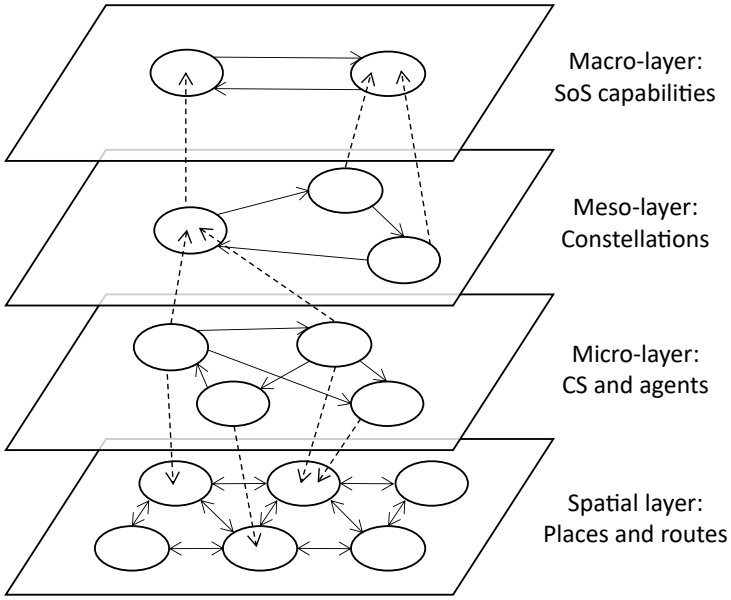

Figure 5. Illustrative example of a layered graph SoS model.

- *Spatial*: Describes the physical space in which the CS and agents are situated and can move (Andrade & Hulse, 2023; Ning et al., 2025; Xu et al., 2025), either as a grid or as a network of places and routes.

Nodes and edges can be given attributes that capture their characteristics and properties. Examples relevant for resilience are failure and repair rates (Chen et al., 2023), node and edge capacity and performance (Chen et al., 2024; Pan et al., 2017), communication quality (Xu et al., 2023), etc. This provides a basis for quantitative evaluations and simulation.

An aspect of particular importance in SoS is its dynamic structure, which also requires having graphs whose nodes and edges change as a function of time (Jiao et al., 2024; Jiang et al., 2024). Examples of dynamic structures in SoS include constellations being formed and dissolved, and CS joining or leaving the SoS (Axelsson, 2019).

2.5 SoS resilience measures

The fourth research question of the literature review addressed which SoS resilience measures are proposed in the literature. Such measures play an important role in understanding the current resilience of an SoS, and for analyzing different approaches to enhancing resilience. Since resilience is about how well the SoS can continue to provide its functionality or services when facing disturbances, a resilience measure should quantify how much its performance and capabilities are affected. However, the disturbances mostly affect the elements of the SoS, so a correspondence must be established between measures on different abstraction levels, as captured in the models discussed in Section 2.4.

This section starts with a description of different performance measures, followed by some approaches to characterizing disturbances. Then, these factors are combined into measures of overall resilience, and finally, approaches for evaluation of the measures are discussed.

2.5.1 Performance measures

Many different types of measures and indicators are available to characterize properties of a system. A first classification is to distinguish between effectiveness and technical performance. Effectiveness indicates how well the system as a whole achieves its operational objectives, and it is thus a macro-level measure which is expressed from the user's perspective disregarding the system design. Technical performance, on the other hand, measures physical or functional attributes of the system, and is applicable both on the macro, meso, and micro levels. It thus assumes knowledge about the system structure and takes the perspective of a developer.

In the context of SoS resilience, both types of measures are relevant. Effectiveness measures can be used to characterize the effects of a disturbance on the value provided by the SoS to the user, such as the amount of capability loss (Chen, et al., 2024; Han et al., 2012; Jiao et al., 2024). A concrete example in the context of transportation is the amount of transportation work in a supply chain SoS (Watson, et al., 2022). Technical measures on the meso-level can include the number of different constellations that can be formed (Chen et al., 2024; Ning et al., 2024; Sun et al., 2024), and the actual performance of those constellations (Xu et al., 2025). On the micro-level, the performance of individual CS (Jiang et al., 2024), the performance or quality of communication (Jiang et al., 2024), and the availability of CS (Jiao et al., 2024) are potential technical performance measures.

2.5.2 Disturbance models and measures

Disturbances are typically modeled and measured at the micro-level or meso-level of an SoS and not directly affecting the macro-level capabilities. In the literature, two dimensions are commonly used for characterizing disturbances. The first is based on the location of the disturbance and the second on its nature or cause.

Disturbance locations can be divided into external, i.e., associated with the environment of the SoS, or internal, i.e., mainly resulting from component failures (Klingensmith & Madni, 2017). Then, given that many papers use graph-based SoS models, the location can either be characterized as residing in the nodes or in the edges of the graphs. The nodes are in many models describing the CS of the SoS, and a CS disturbance represents a loss of performance (Andrade & Hulse, 2023; Zhang & Matsubara, 2025). The edges in a graph-based SoS model typically describe communication paths between CS (Han et al., 2025). The graphs can also represent a spatial network, where places and routes may be affected by disturbances or obstacles, rendering them non-accessible (Xu et al., 2025).

The nature of disturbances considers what kind of entities the nodes and edges represent. If they are primarily information systems, cyber-attacks are important disturbances (Han et al., 2023). These can be related to nodes (e.g., software flaws, access vulnerability) and edges (network vulnerability) (Hossain et al., 2020). Other IT-related disturbances relate to interoperability between different systems (Mansouri et al., 2009). Given that SoS represent sociotechnical situations, technical disturbances need to be complemented by those triggered by organizations and humans and those resulting from natural causes (Mansouri et al., 2009). In a resilience assessment framework suggested by Siemieniuch et al. (2015), finance, knowledge, people, organization, software, hardware, information, and logistics are all considered resilience enablers, but also potentially targets of disturbances.

2.5.3 Resilience measures

Resilience measures should indicate the loss of effectiveness of the SoS subject to disturbances (Jiao et al., 2024), thereby allowing a comparison of different solutions to enhance resilience. Effectiveness is a macro-level property whose values depend on the ability to form meso-level constellations made up of micro-level entities, under the constraints of the spatial environment. Also, the disturbances

mainly affect the micro-level entities. Therefore, the macro-level resilience measures are formed by aggregating properties and indicators at lower levels (Watson et al., 2020). However, the response to a disruption is dynamic and undergoes several phases, as described in Section 1.2 above. Therefore, the resilience measures are aggregated over time, considering both the level of capability loss and the duration of the reduced performance (Chen et al., 2024; Xu et al., 2025). The aggregated resilience measures further need to be weighted by the likelihood of different types of disturbances, which builds on both their location and nature, as explained in the previous subsection.

This aggregating approach fundamentally assumes knowledge about disturbances, and hence only applies in the case of specified resilience. For general resilience, this knowledge is unavailable, and an aggregated macro-level resilience measure cannot be derived. Instead, common approaches rely on using technical performance indicators such as network theory metrics (Ed-daoui et al., 2021).

2.5.4 Evaluation approaches

Many measures of resilience are straightforward aggregations of measures on the micro-level or meso-level into the macro-level. Some papers quantify this based on data about, e.g., failure rates and probabilities of events, whereas others also perform qualitative analyses, such as Agarwal et al. (2023) for architecture evaluation. However, in cases where the measure is not a straightforward aggregation, but rather includes dynamic behavior, more elaborate approaches are needed.

A number of papers apply simulation techniques of different kinds. Agarwal et al. (2023) use SysML models to analyze recovery time from specified disturbances. Andrade & Hulse (2023) apply functional models to assess mission success in a wildfire response SoS. Liu et al. (2023) use system dynamics simulations to analyze survivability of a military SoS, by making connections between different factors explicit. Often, a single simulation approach is insufficient. Mostafavi & Abraham (2014) present a hybrid approach combining system dynamics and agent-based simulations to evaluate the effects of different policies.

Most resilience models contain uncertain factors, requiring systematic evaluation of many scenarios. One approach to this is Monte Carlo simulations, where each uncertain factor is described using a statistical distribution (Chen et al., 2024; Chen et al., 2025; Watson & Bras, 2022). In each simulation run, point values are drawn at random from these distributions, and resilience data can be collected and characterized as statistical distributions as well. In a similar fashion, Ning et al. (2025) evaluate resilience of a military SoS under unknown attack scenarios by randomly generating attacks. Uncertainty can also be dealt with using sensitivity analysis, which is applied by Hossain et al. (2020) to parameters of a Bayesian network.

2.6 SoS resilience enhancement

The final research question of the literature review covers what SoS resilience enhancement approaches have been proposed in the literature. The proposed solutions can be grouped based on whether they relate to micro-level, meso-level, or macro-level entities, which is the topic of the first subsection. The second subsection highlights some work that take an architectural design perspective. Finally, in the last subsection, the importance of humans and sociotechnical aspects in achieving resilience is discussed.

2.6.1 Solutions at different hierarchical levels

Based on the hierarchical model of SoS illustrated in Figure 5, the literature proposes enhancements at all levels. Starting with the micro-level, there is a focus on what CS and communication relations to include in the SoS and how to strengthen those. One approach is to increase redundancy by adding more CS or communication links of the same kind (Xu et al., 2024). In this way, if one element fails, the

chances are higher that this can be compensated by other elements. A second approach is the opposite, namely, to remove elements. This may seem counterintuitive but has its place in isolating different parts of the SoS from each other to avoid spreading the effects of a disruption. This is primarily discussed in relation to electricity grids, where connections between sub-grids can be closed to move to island mode operation (Mehrjerdi, 2020; Qin & Liu, 2024). Similar solutions are used in cyberattacks, where severed communication links can stop an intrusion or virus from spreading. However, there is clearly a trade-off here, since disconnecting parts may result in a reduced ability to form useful constellations, thereby reducing the capabilities of the SoS. A third approach is to improve the resilience or performance of individual elements (Hossain et al., 2020; Svenson et al., 2021).

On the meso-level, approaches for improving the formation and reconfiguration of constellations are discussed. When a disruption affects elements in an operational constellation, resilience is primarily achieved by forming new relations, e.g., by replacing the failing CS with another CS from the same constellation; replacing it by a previously passive CS or an active one from another constellation; or repairing the failing CS. Just as on the micro-level, redundancy can be used, by maximizing the number of different ways in which a certain constellation type can be formed (Han et al., 2023). This then ensures that the capability provided by such constellations can be achieved in many ways.

Macro-level entities are primarily the capabilities provided by the SoS, through collaboration among CS within constellations. Many of these SoS capabilities are fundamentally about how to use available resources, which makes decision policies or strategies part of the macro-level concerns. A fundamental capability of a system is viability, i.e., the capability to survive, and it is a prerequisite to being resilient (Siemieniuch et al., 2015). It requires an ability to perceive the nature and scale of the disruption, what CS are no longer capable, and to plan and deliver the restoration capability. To efficiently and effectively provide the restoration capability of the SoS, policies are needed for in which order repairs should be carried out. Functional redundancy and decentralization are important to achieve recovery through self-organization and adaptation (Jiang et al., 2022). Spatially oriented policies that include decisions about the relocation of people or assets to minimize damage are also an option. In the longer-term perspective, resources need to be allocated to enhancing resilience against potential future disruptions (Mostafavi, 2017; Mostafavi & Abraham, 2014).

2.6.2 Architectural design

Whereas most of the approaches discussed in the previous subsection address operational decisions at different levels of the SoS hierarchy, there is also research on architecting for resilience during the preparation phase (see Figure 1). The architectural design space includes what types of CS to include and their communication links (Han et al., 2012), and what roles, functions, and rules should be present at different hierarchical levels (Svenson et al., 2021). The network structure is discussed in many publications, and in particular the trade-offs between distributed and centralized solutions (Andrade & Hulse, 2023). There is also a need for functional redundancy, where the architecture needs to provide alternative ways to perform a particular function without relying on a particular physical system (Klingensmith & Madni, 2017).

2.6.3 Sociotechnical aspects

An alternative distinction of resilience mechanisms is between hard, i.e., based on technology, or soft, which rely on human interventions. In their work on societal resilience, Siemieniuch et al. (2015) view the humans as the most important assets, and trust between them is essential, as is trust in technology. They note that trust requires the establishment of common goals, transparency, benefit sharing, common language, respect for confidentiality, delivery on promises, and recognition of the "favour bank". The development of a culture of trust requires leadership, a communication and IT infrastructure that support information dissemination, processes for normal operation and recovery,

reward structures that encourage collaboration, and empowerment of individuals with local knowledge. In their paper, they discuss perspectives of this on the different hierarchical levels, which in a sociotechnical setting translates to the overall organization at the macro-level, workgroups and projects at the meso-level, and individuals on the micro-level.

Siemieniuch et al. (2015) also view communication and feedback as fundamental. Aggregated data is of limited use, but it is timely, organized, informative, and disaggregated data of ensured quality is essential. The response to a crisis will vary between different phases, from the initial relief effort providing food, water and shelter, to rebuilding the economy. Daily meetings with local teams are required, and especially in the initial phases, the teams need to know a priori what to do to be effective.

Klingensmith & Madni (2017) discusses what tasks are suitable for automation and concludes that skill-based and rule-based tasks with low uncertainty can be automated, whereas knowledge-based tasks and tasks with higher uncertainty are better for humans.

3 Transportation resilience

In this chapter, an initial conceptual model of a road transportation SoS is outlined to support resilience analysis. The input to the model came from a full-day interactive workshop involving experts in transportation, vehicles and services, infrastructure, analysts, and researchers. The aim was to create a description and common understanding of the transportation system, its key capabilities and actors, and different indicators of its effectiveness. This also led to discussions about system boundaries as perceived by different actors. The collected information was then analyzed and refined, partly in follow-up meetings. The chapter begins with a summary of the context and assumptions underlying the analysis, followed by a characterization of key capabilities and elements of the SoS according to each of the layers introduced in Section 2.4.

3.1 Context and assumptions

The scope of the workshop was road transportation, with an emphasis on goods but not excluding people. The participants were based in Sweden but also included persons with experience from other European countries, thereby emphasizing Swedish and European traffic system characteristics. The technology assumption was a moderate extrapolation of today's situation, namely, an increasing but not complete electrification, increasing but not complete use of automation, and extensive connectivity for information exchange with vehicles. A consequence of this is that the analysis was not limited to the actual transportation work but also included related sectors such as energy and telecommunications.

3.2 Macro-level capabilities

A capability is what a system can do, and this is essential to describe in order to analyze resilience, since resilience is about preserving and restoring capabilities when disturbances occur. Capabilities can be described based on their function, properties, and wider influence.

The fundamental capability of the transportation SoS is to perform the function of moving people and goods between places. Resilience is thus about upholding this capability. The purpose of transportation system is to increase mobility, create accessibility, reduce inequalities, and provide efficient supply chains. This has a wider influence on the economic development of society as well as on sustainability and the environment, both on shorter and longer terms. The total volume of transportation is affected by how well it can be performed.

This fundamental capability comes in many variants, depending on what is to be transported, volumes, routes, distances, and various constraints. A fundamental property is its effectiveness, which is often indicated as the time or cost for the transportation, but also as safety, i.e., minimizing injuries to people and damages to property.

This core capability requires several enabling capabilities, both in normal operation, in support of the lifecycle, and to enhance resilience. One enabling capability is to provide road infrastructure, which also includes maintenance. However, infrastructure construction requires large amounts of material transportation, thereby increasing the need for the fundamental transportation capability. Also, construction and maintenance often take place within the existing operational infrastructure. The long-term benefit of an improved infrastructure to better support transportation can thus yield a short-term reduction in transportation capability.

Another enabling capability is to provide energy. Physical movements depend on energy, and this must be supplied to vehicles in the required quantities and locations. For electric vehicles, energy is provided through a dedicated infrastructure, but charging points become a potential bottleneck. For internal

combustion engines, the fuel must be transported by road to filling stations. Disturbances in energy delivery pose a significant resilience threat to transportation. This also indicates another important property of the transportation capability, namely its energy consumption. This affects the cost, but has also other consequences, such as its influence on how much energy is available for other societal sectors, and the effects on the natural environment.

Resilience requires adaptivity, both to operationally adapt transportations to deal with disturbances and to adapt in the longer term to societal and technical development. Adaptivity and flexibility can also mean to choose technical implementations which enable that the same means of transportation can be used for many different purposes and kinds of goods. Future technology, such as automation, self-optimization, and data-driven AI, can increase the system's adaptability. It can also create secondary effects beyond the primary capability, such as letting electric vehicles contribute to balancing the power grid, or through the creation of circular flows.

However, new solutions and capabilities can also have negative effects or provide new risks that must be considered. For autonomous vehicles, minor changes in how vehicles move can have emergent effects, both positive and negative, on the traffic flows. Central IT systems may also be needed for coordination, and these can become potential points of failure. Finally, new technology or increasing redundancy often leads to increasing costs, against which the benefits must be balanced.

3.3 Meso-level constellations

To provide the capabilities in specific situations, different actors need to collaborate in constellations (Axelsson, 2019). For the primary transportation capability, this includes supply chains for goods and public transportation route networks for people. For the enabling capabilities, such as road infrastructure provision, constellations are also formed, consisting of various construction machines and bespoke supply chains of material and waste. The formation of constellations is decentralized, which is beneficial for resilience.

To effectively use resources and optimize the performance of the capabilities, information and communication is necessary. This can include current traffic flow measures to allow route choices that improve throughput, which is an emergent characteristic of the SoS.

3.4 Micro-level actors and system boundaries

The transportation system involves, directly or indirectly, a myriad of actors whose capabilities partly overlap. Figure 6 shows a partial set of actor types, arranged according to the "Sombrero" model (Flood & Carson, 1993). In this model, actors are divided into five groups, which are presented in the following subsections.

3.4.1 Nearer system-of-interest

The nearer system-of-interest (SoI) includes the elements of direct interest to the modeler. In this case, the focus is on the transportation work, which contains the following actors:

- In the case of moving people, the transportation operator can be private cars, taxis, or public transportation companies.
- In the case of moving goods, the operator is the hauler.
- The vehicles need staff, in particular drivers. In a future context with autonomous vehicles, it is still likely that staff will be needed, to remotely monitor the operation and intervene when needed.

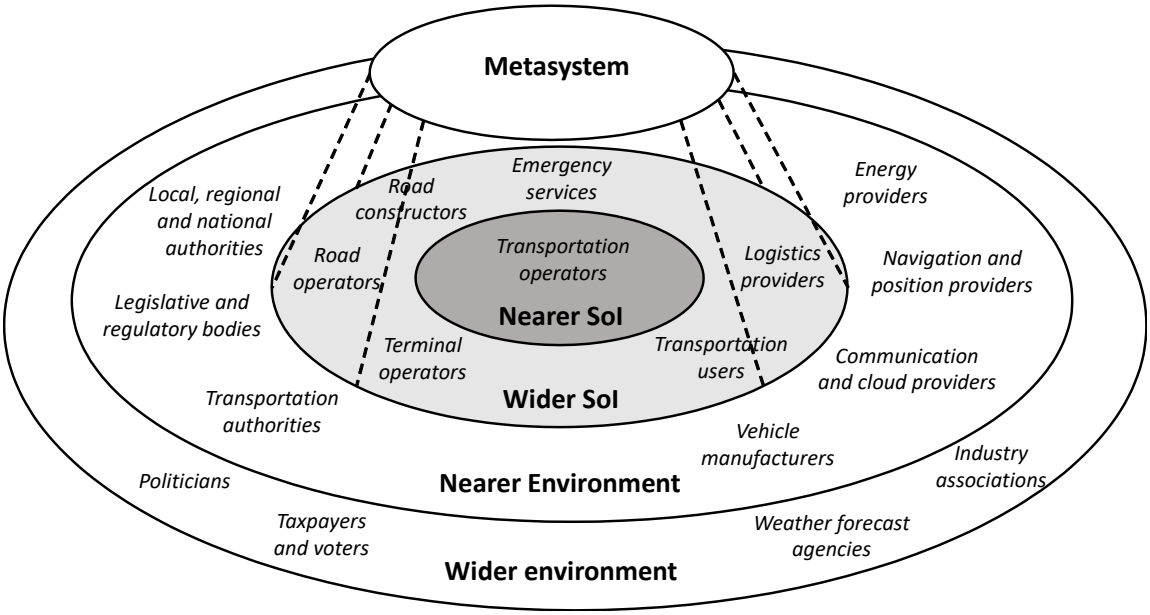

Figure 6. Partial set of transportation SoS actors, arranged according to the "Sombrero" model (Flood & Carson, 1993).

3.4.2 Wider system-of-interest

The wider SoI includes elements needed to support the nearer SoI, which here includes two groups of actors. The first group is involved with the transportation service, and includes the following actors:

- Transportation users, i.e., the people who need to move or the owners of goods.
- For public transportation, there is often an organization responsible for the service (e.g., a municipality or region, or a private company) which acquires the actual transportation from a separate operator company.
- For goods, there are larger supply chains with actors such as logistics, terminals, ports, and goods distributors.
- For multimodal transportation, there are also transportation service suppliers who coordinate the whole itinerary.

The second group is involved with ensuring that the road infrastructure is functioning, and includes:

- Road operators who own the road and ensure their status in the short term (e.g., snow removal) as well as long term (e.g., repairs, asphalt renewal). Road operators can be national, municipal, or private.
- Road constructors build new roads on commission from the road operators, and maintain current roads based on assessments of their conditions.
- Emergency services contribute to safety by taking care of those injured in accidents.
- Roadside assistance services similarly contribute by removing malfunctioning vehicles that would otherwise interfere with the flow of traffic.

3.4.3 Nearer environment

The nearer environment includes elements with which the wider SoI interacts directly. This includes three groups of actors. The first consists of different authorities:

- Legislative and regulatory bodies. These are organized at different levels, from the EU to national, regional, and municipal levels.
- Authorities, who control various sectors based on general directives from the legislative and regulatory bodies. In Sweden, this includes the Swedish Transport Agency (Transportstyrelsen), which also has an operative role when it comes to transportation that requires special permissions and for dangerous goods; the Swedish Civil Defense and Resilience Agency (MCF); the armed forces; the county boards, who are responsible for certain aspects of resilience; and municipalities and cities.
- Certain authorities also act as procurers of services and infrastructure, which includes planning of investments and maintenance, and real-time traffic control.

The second group of actors includes providers of the means of transportation, with the following actors:

- Vehicle manufacturers.
- Energy producers, which include power plants for electricity and oil refineries for fossil fuels.
- Energy distributors, which include grid operators for electricity and fuel transportation for fossil fuels.
- Energy point of sales, which include charging point operators for electricity and filling stations for fossil fuels.

The third group relates to digital services, and includes:

- Telecom operators.
- Positioning services, such as GPS.
- Map and navigation providers.
- Cloud and data storage providers.
- Data owners, which raises issues related to data sharing.

3.4.4 Wider environment

The wider environment consists of elements not directly interacting with the wider SoI but still influencing its behavior. This includes the following actors:

- The general public, who elect politicians and contribute with tax funding.
- Politicians who are elected for the legislative and regulatory bodies.
- Landowners, on whose property roads and other infrastructure are constructed.
- Weather forecasting services.
- Actors contributing to the development of the transportation system, such as innovation support, investors and funders, researchers, and standardization bodies.
- Organizations that group individual actors, including trade unions, employer organizations, and industry associations.
- Governments in other countries with a large influence on technology development, geopolitics, etc.
- Natural phenomena and events, e.g., related to climate, pandemics, etc.

3.4.5 Metasystem

The metasystem consists of the actors who exercise control of the wider SoI. There is no apparent metasystem in this case, indicating that it is a collaborative or virtual SoS with no central controller (Maier, 1996).

3.4.6 Boundaries

Some of the concrete actors were difficult to classify according to the five categories of the Sombrero model. This included municipalities and cities, terminals, ports, and goods suppliers. This is because they play several roles in the SoS, and a more detailed analysis is needed to describe this in detail. Different actors may also view the whole SoS differently, which could influence if they would be considering themselves to be, e.g., in the nearer or wider environment.

It is worth noticing that the above description involves many actors who are not traditionally associated with transportation. However, the boundaries between sectors are blurring as technology evolves. As an example, with electric vehicles, energy is not just going into the transportation system. With vehicle-to-grid technology, energy stored in vehicle batteries can be fed back to provide grid balancing services or support in peak load situations. This increases complexity considerably in deciding how to use vehicles, which in turn affects information and communication needs, and requires more advanced data-driven decision support.

3.4.7 Actor characteristics

Although the actors above interact in various ways, they are also independent agents with their own decision-making and their own incentives and priorities (Axelsson, 2026). This is a key characteristic of an SoS and is what defines the CS independence. To exemplify, a transportation user might wish to get the goods as fast as possible to their destination. The transportation operator may, on the other hand, prioritize cost minimization by ensuring maximum load in each vehicle, which could lead to delays. For the road operator, finally, overall traffic flow is more important than the speed of a particular vehicle, and there is also a trade-off between current traffic efficiency and adapting the infrastructure by constructing additional capacity. All this is positive for resilience in the sense that decision-making is distributed, and there are many ways of providing a certain capability. However, it can also make the response to a disturbance less effective due to a lack of coordination.

Given the varying priorities and responsibilities of actors, they also require different information and indicators to support their decisions on what actions to take. For example, the road operator would require indicators about the functioning of the infrastructure, such as weather events (and in the longer term, climate changes to plan preventive actions), wear, incidents, sabotage and war, and electricity disruptions (affecting, e.g., traffic lights).

3.5 Spatial aspects

Transportation is inherently related to the spatial structure of the environment, both in terms of the starting and ending points of any transportation need, and in terms of available routes between places. It is common practice to model the road infrastructure through network models and use these to analyze current capacity as well as the need for investments (which is discussed further in Chapter 4).

During operation, the status of the road network, in terms of ongoing roadworks, congestion, and accidents, is essential for routing decisions. With the increasing use of information and communication technology, the positions and movements of individual vehicles can be monitored and used for route guidance. Route information, such as snow conditions, is essential for allocating resources, e.g., plowing vehicles.

Road safety is also related to spatial characteristics, although much more locally. The most fatal accidents involve collisions between vehicles, which is a spatial conflict.

4 A KPI framework for transportation infrastructure resilience

In resilience engineering, measures of effectiveness and performance are essential to guide improvement activities, as discussed in Section 2.5 above. Resilience measures for SoS are typically defined based on effectiveness of capabilities in the macro layer. Their values are derived by aggregating various key performance indicators (KPIs) on the meso, micro, and spatial layers of a hierarchical SoS model, as previously depicted in Figure 5. The aggregation also considers the resilience phases of absorption, recovery, and adaptation (see Figure 1), thereby reflecting both system performance loss and system dynamic response across these phases.

A transportation SoS is increasingly exposed to a combination of predictable and unpredictable disruptions, ranging from climate-related events and infrastructure failures to supply-chain shocks, cyber incidents, and energy system disturbances. As digitalization, automation, and electrification advance, further interactions and potential disruptions emerge. Therefore, it is essential to consider what KPIs are relevant to analyze the resilience of future transportation SoS, which is the topic of this chapter. The KPIs relate to traditional disturbances, such as road closures, congestion, capacity limitations, as well as emerging SoS-related disruptions, including:

- *Electrification-related risks*, e.g., charging infrastructure bottlenecks, energy availability.
- *Digital and cyber disruptions*, e.g., navigation, communication loss.
- *Geopolitical and supply-chain disruptions*, e.g., fuel distribution, logistics shocks.
- *Climate-driven events*, e.g., flooding, heat, storms.

The chapter starts with an overview of KPIs that enable planners to evaluate the absorption, recovery, and adaptation capacity of transport systems under disruptive conditions. Preparation is often included as baseline in transport planning without specific KPIs. Then, several tools and analytical methods currently used in infrastructure planning and policy development are evaluated to understand their usefulness for resilience engineering. Particular attention is given to the *Sampers* tool (Kristoffersson et al., 2018), which is widely used for infrastructure planning in Sweden. Finally, some implications for infrastructure planning and research are identified.

4.1 Absorption phase KPIs indicating robustness

Robustness KPIs quantify how well the system continues to function immediately after a disruption. They are closely aligned with traditional vulnerability studies but broadened through a SoS lens.

The first three indicator groups align with how Sampers produces traffic-flow charts, accessibility maps, and mode-choice outputs. More details can be found in the discussion on the brute-force method in Section 4.4.1 below.

Across all indicators, loss is defined as the deviation between performance under a disruption scenario and the baseline (normal operating) scenario. This comparative approach makes it possible to quantify the magnitude, spatial pattern, and system-level consequences of disruptions.

4.1.1 Network performance loss

- *Δ Travel Time (ΔTT) per origin-destination (OD) pair or corridor*: ΔTT measures performance degradation relative to baseline scenario.
- *Δ Throughput / Link Utilization Change*: This identifies critical links where reduced capacity has disproportionate system impact.
- *Remaining Network Capacity (%)*: This calculates the ratio of available link capacity to normal conditions after the disruption.

4.1.2 Accessibility and connectivity

- *Accessibility Loss (%)*: Share of population/jobs reachable within a given travel time threshold compared with baseline.
- *Reduction in Reachable OD Relations*: Number of OD pairs that exceed acceptable travel times.

4.1.3 Modal and routing adjustments

- *Transport mode Shift Intensity*: Change in transport mode shares caused by disrupted routes or infrastructure.
- *OD Demand Served (%)*: Share of total demand that can still be feasibly transported.

4.1.4 Charging queue elasticity (CQE)

This index measures how sensitive queueing times are to increases in charging demand during peak periods or partial outages. While queueing-related metrics exist in the indicator inventory, elasticity adds a new behavioral dimension and provides a clearer view of system robustness under stress. This indicator can be individually analyzed using micro simulation or with statistics modelling for average estimates.

4.2 Recovery phase KPIs

Sampers is a static equilibrium model and does not explicitly simulate the temporal dynamics of disruption or recovery following climate- or weather-related impacts. As a result, recovery processes cannot be modelled directly over time. Instead, recovery-related key performance indicators (KPIs) must be inferred through scenario-based or comparative analyses, for example by comparing model outcomes before and after the affected road segments are degraded, restricted, or restored. In this way, Sampers can be used to assess changes in accessibility, travel behavior, and system performance associated with different disruption and recovery states, even though the recovery process itself is not dynamically represented. Relevant KPIs are:

- *Accessibility Recovery Index*: The index measures the share of previously lost accessibility restored when moving from baseline or “disrupted” to “restored” scenario.
- *OD Travel Time Recovery (%)*: Quantifies how much of the travel time degradation is resolved between baseline or “disrupted” and “restored” scenario.

These KPIs provide signals even though Sampers does not include dynamics; they serve as proxies for recovery capacity in planning contexts.

4.3 Adaptation phase KPIs indicating long-term resilience

Adaptation metrics relate to the system's ability to evolve and become resilient to future, possibly unknown disruptions.

- *Redundancy and Diversity*: Redundancy includes the number of alternative paths available for key OD relations. Diversity can be inferred as the number of different transport modes serving critical flows.
- *Charging Infrastructure Readiness Index*: This index can directly support analysis of minimum spacing/allocation compliance deficits according to EU regulations compared with existing charging infrastructure. The index can also be extended considering the long-term attractiveness of a location for private charging infrastructure investment, incorporating freight demand, grid accessibility, and existing operator competition.

- *Structural Adaptability*: Potential to reroute traffic or modify service patterns under new constraints.

4.3.1 Flexibility for introducing new modes or services

These indicators reflect insights from the SoS perspective, where actor independence, lack of centralized control, and emergent behavior strongly influence resilience.

4.4 Using Sampers for KPI estimation

As mentioned previously, Sampers is widely used for passenger transport forecasting and infrastructure assessment in Sweden. Here, its suitability for resilience analysis is discussed, starting with a simulation method to capture perturbation effects. Then it is indicated how Sampers outputs can be mapped to the KPIs introduced above, and finally, some strengths and limitations are highlighted.

4.4.1 Brute-force method

WSP employs a brute-force simulation method in which parameters are systematically perturbed - capacity reductions, travel time increases, or partial network removals - to explore a broad set of disruptive scenarios. This approach:

- does not require predefined disruption probabilities,
- supports analysis of unknown or poorly understood events,
- reveals emergent behaviors and system thresholds,
- can be complemented with infrastructure network topology analysis, e.g., connectivity, centrality and redundancy.

4.4.2 Mapping Sampers outputs to KPIs

Sampers produces origin-destination (OD) matrices, modal splits, flow charts, and accessibility indicators on different scenario that can map directly onto:

- travel time degradation → ΔTT, OD service reduction,
- flow redistribution → network load change,
- accessibility outputs → accessibility loss and recovery,
- mode shifts → modal resilience,
- user responses → emergent meso-level constellations.

This creates a structured, model-based assessment of robustness and partial recovery, even though dynamic recovery is not modelled explicitly.

4.4.3 Strengths and limitations

Using Sampers for KPI estimation has several strengths:

- Capable of capturing emergent macro-level effects of local failures (transport system behavior).
- Suitable for exploring scenarios without predefined disruption probabilities.
- Scalable to national-level analysis.

However, Sampers also has certain important limitations:

- Lacks time dimension, cannot model dynamic recovery processes.
- Interdependent systems (energy, telecom, logistics) must be treated as scenario inputs rather than integrated dynamic elements.

- Stakeholder behavior is represented through equilibrium choice models, not adaptive learning or heterogeneous priorities.

Nevertheless, Sampers offers a robust baseline for resilience KPI assessment.

4.5 Other tools

Several other types of tools exist to complement Sampers. Here, two WSP tools for resilience and e-mobility analysis are discussed, followed by a review of how system dynamics can be used for transportation applications.

4.5.1 WSP resilience tools

WSP UK has developed a set of structured resilience assessment tools used to evaluate how transport networks respond to shocks and stresses. Key features include:

- *Leadership & governance*: Helps organizations embed resilience thinking, clarify roles, and improve cross-departmental decision-making in daily corporate operation.
- *Asset management integration*: Connects resilience scoring with asset condition, maintenance planning, and lifecycle strategies.
- *Risk & vulnerability assessment*: Identifies critical assets, dependencies, and exposure to climate and operational risks.
- *Prioritization frameworks*: Supports ranking of interventions and investment options.

4.5.2 WSP e-mobility planning tools

WSP's e-mobility planning toolkit provides a strategic, comprehensive, data-driven approach for planning public charging infrastructure for heavy-duty electric road transport across Europe. Built to address the rapid growth of freight electrification and the complex dependencies between transport systems and energy networks, the toolkit supports strategic planning, regulatory compliance and investment decision-making. Rather than general forecasting of traffic flows as in Sampers, the focus is on infrastructure feasibility, capacity needs and system bottlenecks under different development scenarios specific to public charging infrastructure for heavy-duty vehicles.

Purpose and scope

The toolkit identifies optimal locations and required capacity for e-truck charging along major freight corridors. It integrates freight transport patterns, energy system constraints, and regulatory requirements to ensure that charging networks are both feasible and future-proof. The platform is designed to assist infrastructure owners, authorities, energy companies and charging point operators. Analyses are based on the following input:

- Freight flow data
- Assumptions on electrification rates and vehicle energy performance
- Power grid availability, connection capacity and upgrade needs
- Regulatory constraints and policy targets (e.g., the Alternative Fuels Infrastructure Regulation, AFIR)

Key analyses and indicators

The tools generate a set of infrastructure- and energy-oriented KPIs, including, e.g., the Charging Infrastructure Readiness Index (see Section 4.3).

The e-Mobility planning tools are intended to support strategic planning and risk assessment for public charging infrastructure, rather than detailed traffic assignment or traveler behavior modelling.

Benefits for stakeholders

- Public authorities gain a clear picture of charging needs and can plan infrastructure roll-out aligned with freight demand and EU regulations.
- Distribution system operators (DSOs) and energy providers can anticipate grid reinforcement needs and prioritize upgrades where charging demand will be highest.
- Charging point operators (CPOs) receive a structured view of investment opportunities, demand hotspots, and areas with strong commercial potential.
- Logistics operators and OEMs benefit from insights into future corridor capabilities, enabling strategic fleet transition planning.

Overall value

The e-Mobility planning toolkit provides a unified platform linking freight transport demand, charging infrastructure, power system and regulatory requirements. It reduces silo perspective, accelerates integrated planning, and supports evidence-based investments in public charging infrastructure. By combining optimization, energy assessment and strategic decision support, it delivers a robust foundation for the electrification of heavy-duty transport across Europe.

4.5.3 System dynamics

System dynamics is a generic modelling approach useful also for SoS resilience in general (Mansouri et al., 2009). It is used alongside, but not as a part of, WSP's resilience tools, and provides:

- *Temporal cause-effect modelling*: Shows how disruptions evolve over time, including feedback loops and delays.
- *Scenario design and exploration*: Enables multiple stakeholders to actively participate in the co-creation of future scenarios by identifying key drivers, uncertainties, and policy levers. The approach supports structured discussions about which factors are most influential, how they interact, and how cause–effect relationships evolve across the system. By exploring alternative assumptions and interventions, stakeholders can jointly test policies, operational strategies, and high-level network behaviors, gaining insights into feedback loops, trade-offs, and unintended consequences under different future conditions.
- *Stakeholder-friendly visualization*: Makes complex system behavior intuitive, improving understanding and dialogues.

4.6 Implications for infrastructure planning and research gaps

The KPI framework supports planners in:

- Identifying critical corridors and bottlenecks with disproportionate system impact.
- Assessing investment needs that improve robustness or redundancy.
- Mapping electrification-related vulnerabilities (charging demand, grid constraints).
- Stress-testing of climate adaptation strategies.
- Understanding the consequences of digital dependencies.

However, several knowledge gaps remain:

- Need for improved integration of energy system models and digital infrastructure data.
- Need for dynamic modelling capabilities to capture recovery processes.
- Insufficient methods for evaluating stakeholder misalignment and SoS governance issues.
- Limited availability of empirical data on rare disruptive events.

5 Catalogue of resilience indicators

The previous chapters have shown that resilience in road transport cannot be assessed only by studying the road infrastructure as an isolated technical system. Road-based freight transport is increasingly dependent on several coupled systems, including energy supply, charging infrastructure, digital connectivity, automation functions, logistics platforms, infrastructure operators, and public authorities. This is particularly evident for electrified, connected and automated freight transport, where the transport capability depends not only on roads and vehicles, but also on the availability of charging power, data exchange, positioning services, cyber-secure platforms, and coordinated operational decision-making.

The project has conducted research on a structured basis for assessing resilience in such a transport system-of-systems, i.e., a resilience indicator catalogue. The catalogue does not aim to define a single universal resilience score. Instead, it identifies groups of indicators that can be used to describe how a transport capability is affected before, during and after disruptions. The catalogue therefore supports several uses: identifying critical dependencies, comparing disruption scenarios, selecting indicators for future modelling work, and guiding the design of follow-up studies. While this is a very preliminary catalogue, it serves as a basis for further refinement based on the needs of the stakeholders.

In the project, the focus is on surface freight transport with particular attention to emerging trends such as electrification, connectivity, and automation. However, many of the indicators are also relevant for conventional road freight and for broader transport infrastructure planning. The full indicator catalogue is maintained as a separate living inventory. This chapter summarizes the structure and main indicator groups.

5.1 Method for identifying and structuring indicators

The indicator catalogue was developed through an iterative synthesis of the project's SoS perspective, the transport resilience literature, workshop findings, and the specific challenges associated with electrified, connected and automated freight transport. The process followed four main steps.

First, resilience was framed according to the phases introduced in Section 1.2, namely preparation, absorption, recovery, and adaptation. This ensured that the indicators cover not only normal-state preparedness or post-event recovery, but also the system's ability to maintain partial function during a disruption and learn from disruptive events over time.

Second, the transport system was interpreted as a layered cyber-physical SoS. In this framing, transport performance emerges from interactions between several dependency layers. The catalogue therefore separates indicators according to the following layers: transport, energy, digital, cyber, automation, logistics, human/organizational, and cross-system effects. This distinction is important because a disruption may affect transport performance indirectly through another layer. For example, a power outage may first reduce charging capacity, then create queueing at remaining charging sites, which subsequently causes freight delays and lower demand fulfilment.

Third, indicators were categorized by their analytical role. Some indicators describe direct performance, such as travel time reliability or trip completion rate. Others describe capacity, such as redundancy or available charging power. A third group captures risk and vulnerability, such as critical link dependency or asset vulnerability. Finally, a separate group consists of resilience-curve metrics, such as residual performance, performance loss area, and time to recover. This distinction avoids mixing general system attributes, measurable operational KPIs, and model-derived resilience metrics.

Fourth, each indicator was linked to possible analysis methods and data needs. This was necessary because indicators differ substantially in how they can be calculated. Some can be derived directly from operational data, such as GPS traces, charger logs, or dispatch records. Others require network analysis, scenario analysis, system dynamics, simulation, or expert assessment. This step was included to make the catalogue usable for future modelling work rather than only as a conceptual list.

5.2 Indicator classification framework

The catalogue uses several complementary classification dimensions. These are summarized in Table 1.

This structure makes it possible to filter indicators for different analytical purposes. For example, a study focused on freight electrification can filter for energy-related and charging-related indicators. A study focused on cyber-physical risk can filter for digital, cyber, and automation indicators. A transport infrastructure planning study can focus on network, accessibility, travel time, capacity, and redundancy indicators.

5.3 Indicator groups

The catalogue includes indicators across eight main system dependency layers. The most important groups are summarized in Table 2. The table is illustrative rather than exhaustive.

A key finding from the indicator work is that traditional transport resilience indicators remain necessary but are no longer sufficient. Indicators such as travel time reliability, network redundancy, capacity loss, and restoration time remain fundamental for assessing the transport layer. However, electrified, connected, and automated freight transport introduce additional critical dependencies. Charging availability, grid constraints, telecom availability, cyber resilience and fallback automation

Table 1. Main classification dimensions used in the indicator catalogue

Dimension	Purpose	Example values
Resilience phase	Shows where the indicator contributes in the resilience process	Preparedness, absorption, response, recovery, adaptation, curve summary
System dependency layer	Identifies which system layer the indicator primarily describes	Transport, energy, digital, cyber, automation, logistics, human, cross-system
Indicator type	Distinguishes the analytical role of the indicator	Direct, outcome, capacity, risk, composite, curve metric
Analysis method	Describes how the indicator can be calculated or modelled	Network analysis, scenario analysis, resilience curve analysis, statistical analysis, event log analysis
Required data	Identifies data needed for operationalization	Road network data, GPS traces, charger logs, grid data, cyber incident logs, shipment records
Data availability	Supports feasibility assessment	Available now, available with integration, derived/modelled, needs new sensing, external only
Disruption relevance	Links indicators to disruption types	Flood, power outage, telecom outage, cyberattack, charging outage, heatwave

Table 2. Overview of main indicator groups

System dependency layer	Main indicators focus	Representative indicators
Transport infrastructure and network	Physical network robustness, capacity and connectivity	Network redundancy, critical link dependency, shortest path availability, remaining capacity, restoration time
Transport operations	Operational service continuity and performance	Travel time reliability, average delay, trip completion rate, reroute response time, dispatch adherence
Logistics and freight service	Ability to serve freight demand and manage flow disruptions	Demand served ratio, on-time delivery rate, backlog size, terminal dwell time, inventory buffer coverage
Energy and charging	Availability and robustness of charging and grid-dependent freight operation	Charging point availability, charger uptime, queue wait time, power availability ratio, time to restore charging capacity
Digital connectivity	Communication and data availability for connected freight systems	Connectivity uptime, network latency, packet loss, platform availability
Cybersecurity	Ability to detect, contain and recover from cyber-related disruptions	Cyber incident detection time, isolation time, false alarm rate, information system resilience score
Automation	Safe degraded operation and reliability of automated functions	Fallback mode success rate, automated driving disengagement rate, positioning service availability
Human and organizational capability	Workforce, coordination and decision-making capacity	Operator availability, cross-trained staff share, drill completion rate, decision time, stakeholder coordination readiness
Economic and environmental effects	Wider consequences of disruption and recovery	Disruption cost per ton-km, cumulative delay cost, CO_2 increase during disruption
Resilience curve metrics	Cross-cutting metrics describing performance over time	Maximum performance drop, residual performance, performance loss area, time to minimum performance, time to 90% recovery, recovery slope

capability can become limiting factors even when the road infrastructure itself remains physically available.

This observation is important for the SoS framing in this report. Resilience failures may propagate through system layers. For example, a telecom outage may degrade fleet coordination and charging scheduling, which may then reduce delivery reliability. A heatwave may affect both road infrastructure and grid demand, causing charging bottlenecks. A cyberattack may not damage roads or vehicles physically, but may still reduce freight capability by affecting dispatch, charging access, data integrity, or automation functions.

5.4 Disruptions and indicator relevance

The catalogue distinguishes between indicators and disruptions. This distinction is important because one indicator may be relevant for many disruption types, and one disruption may affect many indicators. For example, travel time reliability may be relevant under flooding, snow, congestion, road

closures, and cyber-induced dispatch degradation. Charging point availability may be relevant under power outages, charging platform failures, heatwaves, and grid capacity constraints.

The disruption taxonomy used in the catalogue includes three broad time profiles:

1. *Acute shocks*, such as floods, snow events, crashes, power outages, telecom outages, cyberattacks, and terminal failures.
2. *Chronic stressors*, such as persistent heat stress, asset aging, deferred maintenance, chronic grid capacity shortage, persistent charging congestion, recurring supplier fragility, and skills shortages.
3. *Compound or cascading disruptions*, such as flooding combined with power outage, heatwave combined with grid strain and charging congestion, or cyberattack combined with charging platform outage.

This distinction is particularly important for climate-related resilience. Climate change should not only be represented as an increase in acute hazards. It may also change baseline operating conditions, accelerate asset degradation, increase stress on energy systems, and create repeated or compound disruptions. For this reason, the disruption taxonomy includes long-term stressors and compound events, not only isolated incidents.

5.5 Resilience curves

Many indicators in the catalogue can be interpreted through resilience curves. A resilience curve describes how a selected performance measure changes over time before, during and after a disruption. The catalogue therefore separates raw performance indicators from curve-derived summary metrics, as exemplified in Table 3.

For example, travel time reliability, network throughput, charging availability or the demand vs. served ratio can be used as the performance measure in a resilience curve. From that curve, additional summary metrics can be derived, such as maximum performance drop, residual performance, performance loss area, and time to recovery.

This separation is important because different indicators answer different questions. A raw indicator describes what is happening in the system. A curve metric describes how strongly and how long the system is affected. For example, two disruptions may have the same maximum performance drop, but very different recovery times. Conversely, two disruptions may have similar recovery times but very different total performance loss over the disruption period.

5.6 Future modelling and data collection

The indicator catalogue shows that future resilience analysis will require more than traditional transport data. Road network models, traffic flow data and travel time data remain essential, but they must increasingly be complemented by energy, digital, cyber, logistics, and organizational data. Further modeling and data collection needs are as follows.

First, transport models such as Sampers (see Section 4.4) can support analysis of network and accessibility impacts, especially under scenario-based perturbations. However, they do not directly model dynamic recovery processes or interdependent energy, telecom, and logistics systems. These dependencies must either be represented as scenario inputs or addressed using complementary tools.

Table 3. Examples of raw indicators and resilience-curve summary metrics

Raw performance indicator	Possible curve-derived metrics
Travel time reliability	Maximum drop, recovery time, performance loss area
Network throughput	Residual performance, recovery slope
Demand served ratio	Time to 90% recovery, cumulative loss
Charging availability	Time to restore charging capacity, minimum retained capacity
Connectivity uptime	Duration below service threshold, recovery time
On-time delivery rate	Backlog accumulation and clearance time

Second, electrified freight requires integration with charging and grid data. Indicators such as charging point availability, queue wait time and power availability ratio require data from charging point operators, energy management systems, fleet telemetry and grid operators.

Third, connected and automated freight systems require access to digital and cyber-physical data. Connectivity uptime, latency, packet loss, positioning availability, fallback mode success and cyber detection time require logs from vehicles, fleet platforms, telecom systems, automation stacks and cybersecurity systems.

Fourth, logistics resilience requires operational data from transport management systems, order management systems, warehouse systems, and terminal systems. Indicators such as demand served ratio, on-time delivery rate, backlog size and terminal dwell time cannot be assessed from infrastructure models alone.

Last but not least, several important indicators require cross-actor data sharing. This is itself a resilience challenge in an SoS context, because actors are independent and may have different incentives, data ownership models, and operational priorities.

5.7 Summary and next steps

This chapter presents an initial catalogue of resilience indicators that could be considered for future assessment of road freight resilience in an electrified, connected, and automated transport system. The main contribution is not a fixed list of KPIs, but an initial framework for organizing indicators across resilience phases, system dependency layers, disruption types, analysis methods, and data requirements. Significant further studies are needed to validate the indicators with stakeholders, evaluate the data readiness for calculating related indicators, as well as to creating a systematic process to monitor and follow the resilience indicators.

6 Challenges and knowledge gaps

In the previous chapters, general techniques for SoS resilience modeling and analysis have been elicited and applied to transportation. Additionally, a commonly used technique for predicting indicators of transportation was described, and various indicators of transportation resilience were suggested. Although there is thus a foundation of available methods and knowledge, the results also point towards several gaps and challenges, which are summarized and discussed in this chapter.

6.1 Specified vs. general resilience

As discussed in Section 2.3, there are two alternative worldviews on resilience, which are referred to as specified and general resilience (Cavallo 2014; Cavallo & Ireland, 2014). Specified resilience, which is dominating the literature, assumes at least some knowledge about the type of disturbances that can occur, whereas general resilience does not assume such knowledge.

It can be argued that specified resilience is equivalent to risk analysis, for which methods applicable to SoS have been proposed (Axelsson & Kobetski, 2018). A risk analysis typically consists of two steps. The first is identifying that a certain risk exists, which also includes a qualitative description of where in the SoS the risk applies. The second is to characterize the risk further, which can include a quantification of, e.g., severity and likelihood of occurrence. Many studies in the literature on SoS and resilience assume that such a quantification can be made, but with little discussion on where to get reliable data on disruptive and potentially rare events to support this. There are also challenges related to the dynamic structure of an SoS, which requires investigation of many different scenarios (Pettersson et al., 2023).

General resilience does not assume knowledge about the nature of future disturbances and therefore needs to be addressed using methods from systems thinking and complex systems. Key characteristics include diversity, efficiency, adaptability, and cohesion (Fiksel, 2003) – characteristics which align well with those often used to describe SoS (Boardman and Sauser, 2006). Providing an aggregated metric of resilience is not possible when disturbances are unknown. Instead, network metrics of the SoS model can be used as indicators of resilient patterns (Chen et al., 2025), such as centrality of control, redundancy, etc.

It should be noted that contemporary risk analysis methods, such as STAMP (Leveson, 2011), explicitly discard the possibility to quantify probabilities of risks in complex systems. Since many of the proposed resilience measures are based on aggregating the probability and effects of risks, a consequence is that resilience cannot be easily measured, at least not for complex, real-world SoS. A further argument in this direction is that macro-level behavior that emerges from the behavior of micro-level systems are hard to calculate due to the complex interactions of the CS. Therefore, a measure of SoS resilience by simple aggregation from micro-level properties is unlikely to reflect reality.

In a real setting, all disruptions are not likely to be equal in nature. Some have occurred before and are thus known and possible to include in the qualitative analysis. Certain of those may appear on a regular basis, giving at least some foundation for quantification. Therefore, the best approach in practice is a combination of risk analysis, when possible, and general resilience as a complement. The largest challenge in this, and where research attention should be directed, lies in the general aspects of resilience.

6.2 Analysis methods and indicators

The complexity of the transportation SoS demands that analyses be conducted on a larger scale, for instance, using a national transportation model such as Sampers (see Section 4.4). At the same time,

this means that data from connected systems (e.g., power or fuel) is given as constants and that the dynamic development over time, as a disturbance occurs and the system "responds", cannot be discerned.

Sampers is a so-called equilibrium model, in which everybody has perfect information on available alternatives, and choices are optimized accordingly. The performance of the system can be evaluated in terms of changes in, e.g., travel time, operational costs, pollution, and accidents from before to after an incident. However, the initial "shock" or the adaptation over time between the two steady states remains unknown. An important question also arises due to the variety of stakeholders and their varying priorities: Which function(s) are we aiming to preserve and/or restore? Addressing these issues is vital for the continued work within the field, to avoid focusing on what can easily be measured, rather than what really matters. As was shown in Chapter 5, there is an almost endless number of possible indicators, and managing and selecting from these can easily become an overwhelming task.

6.3 Stakeholder perspectives

A defining SoS characteristic is the operational independence of the participating CS and actors (Maier, 1996), giving them a certain autonomy (Boardman & Sauser, 2006). This means that they decide on their own actions, that they have different world models, and that they can have different notions of value to guide those decisions (Axelsson, 2026). Resilience is about preserving value, which in an SoS corresponds to available capabilities. This perspective of independence is essentially missing from the literature, and instead, papers typically treat the CS as technical entities without willpower, thus ignoring all the mechanisms needed for decision-making and autonomy.

If the SoS participants have different notions of value, they cannot, in general, be assumed to agree on what to prioritize when it comes to dealing with disturbances or investing in enhancing resilience. Many papers on SoS and resilience implicitly or explicitly assume a directed SoS with agreement on objectives. Therefore, there is a knowledge gap in how to deal with different stakeholder perspectives, and how to perform trade-offs between their, often tacit, notions of value. This also holds for different groups in society, including gender groups.

With technological advancement, the roles of stakeholders in emerging transportation systems are evolving. With increasing electrification, automation, and digitalization, as well as innovative business models, stakeholders traditionally working in one domain may start to expand to other domains. This changes the SoS landscape and introduces dynamics in system transformation.

6.4 Sociotechnical aspects

Although decision-making is increasingly supported by automated systems, in the end there is always a human involved, especially for knowledge-based tasks (Klingensmith & Madni, 2017). This makes SoS inherently sociotechnical, and yet, this perspective is not prevalent in the literature, although there are a few exceptions. Instead, there appears to be an overreliance on technology and data, such as digital twins (Smati et al., 2025), which is both unrealistic when it comes to availability of data and creates new vulnerabilities.

While humans and organizations can create difficulties in achieving resilience due to unaligned objectives and can make mistakes, they are also instrumental in dealing with unexpected situations. Human knowledge is an important asset, as is their flexibility, adaptability, and ingenuity (Siemieniuch et al., 2015). Not the least, they can perform abductive reasoning to generate new hypotheses to explain unforeseen situations (Cavallo & Ireland, 2014). To properly capture the nature of human activity systems, there is room for more research that leverage established methodologies such as

Checkland's soft systems method (Checkland & Poulter, 2006) or Jackson's critical systems thinking (Jackson, 2024), to properly acknowledge the differences in objectives of different actors.

6.5 Cost and benefit of resilience

Apart from people and organizations, finance is an important enabler for resilience (Siemieniuch, 2015). However, even with strong finances, resources will need to be prioritized. Trade-offs are needed, both between different alternative resilience enhancements and between resilience and other aspects. However, they are difficult to resolve objectively but must be based on subjective judgments.

The challenge is that resilience is difficult to measure adequately, and the less that is known about potential disruptions, the harder it is. Many solutions to improve resilience are costly and given the uncertainty of the extent to which those solutions will actually be used, the uncertain value provided is hard to compare to the more certain costs. This is discussed in the context of highway network investments in (Mostafavi, 2017) but applies to SoS in general.

Costs can be direct investments in additional capacity or similar, but it can also include lower performance in operation. For societal organizations and authorities, the budgets of different areas are communicating vessels, so an improvement in resilience in one domain reduces the resources available in other domains. In a private company, investing more in resilience than competitors can lead to higher costs and lower market attractiveness, which can be as threatening to viability as external disruptions.

A further trade-off exists in deciding how to best use resources allocated to improving resilience. One possibility is to use them locally, to harden CS and communication systems to reduce the immediate effects of a disturbance. Another option is to focus on the recovery phase and provide capabilities and systems aiming at reconfiguring or repairing damaged parts of the SoS. Since many disruptions do not affect the whole SoS at the same time, it can be more effective to pool such resources centrally to some extent and dispatch them to where they are needed, possibly in combination with local fast-response units.

6.6 Management of resilience

The different CS in an SoS are not only operationally, but also managerially, independent (Maier, 1996). This raises issues about how to organize governance and control of the SoS, which can be thought of as its sociotechnical architecture. An implicit assumption in much of the literature is that there is a central controller, but this leaves open many questions related to achieving resilience in more loosely connected and heterogeneous SoS, such as the transportation SoS.

To understand SoS management, a good starting point is cybernetics, i.e., the science of governance and control (Wiener, 1948). Key results from that field include that a controller must have at least as many states as the system it is trying to control (Ashby, 1956), which puts severe limits on what can be achieved by agents with limited perception and communication bandwidth. Under disruptions, this communication may not be available at all. Also, a controller must have a model of the system it is trying to control, and since different CS may have different objectives, they will construct different world models to support their actions (Axelsson, 2026).

Both centralized and distributed control have their advantages and disadvantages. Therefore, in a practical SoS, a combination of central governance and local operational control is often the best. This is also supported by results in management cybernetics, and in particular, Beer's Viable System Model (VSM) (Beer, 1972). The VSM identifies five systems that are needed, namely direct control of

subsystems; coordination between subsystems; distribution of resources and objectives to subsystems; intelligence gathering from the environment; and strategic governance. All these aspects are also relevant in the context of resilience, but the VSM has only seen limited application in the field of SoS (Cederbladh & Axelsson, 2025).

A distinction is sometimes made between first-order and second-order cybernetics (Heylighen & Joslyn, 2001). In the first order, the observer of a system is outside its boundary, whereas in the second order the observer is part of the system and observing it from within. Many studies take a clear first-order perspective on SoS resilience, e.g., Uday & Marais (2015), by explicitly applying systems engineering methods. However, in many ways, the second-order viewpoint is more relevant to sociotechnical systems in general, and SoS in particular (Axelsson, 2025). Second-order cybernetics also highlights that resilience is not achieved by an outsider, but the viability of an SoS must be created from within. This resonates with the concept of autopoiesis (Varela, 1974), whereby a system ensures its integrity by having internal processes that allows it to reconstruct itself.

The results from cybernetics point at the need for identifying capabilities that an SoS needs to have to enhance resilience. Those capabilities would emerge on the macro-level but require constellations on the meso-level and agents on the micro-level to realize them. Often, mediators are required to facilitate the creation and use of these capabilities (Axelsson, 2024). Capabilities, beyond those needed for normal operation, include creating situation awareness about ongoing disruptions and their effects, efficient and effective decision-making for coordinated responses, and the ability to redirect resources to where they are needed. This builds on a capability of modeling and analysis and on a general viability capability, as the SoS must continue to exist in order to provide any capabilities. This includes ensuring that CS have incentives to remain within the SoS (Svenson & Axelsson, 2021). When considering the needed capabilities, a continuous lifecycle perspective is needed (Dreesbeimdiek, 2022) rather than just responding to events, which is further supported by the key SoS characteristic of evolutionary development (Maier, 1996).

6.7 Complexity

Many SoS are highly complex, in particular the ones on a societal scale for which resilience is perhaps of highest importance. This is acknowledged in many studies, but still, the connection to established literature on complexity is poor. Weaver (1948) discussed the complexity of large, but highly organized systems, for which mathematical analysis is applicable, and contrasted this with systems characterized by many similar elements with random distributions, where statistical methods can be used. He concluded that the highest complexity lies in-between these two, where elements are heterogeneous and only partly organized, something which is also confirmed by Gell-Mann (1995). Complexity is strongly associated with non-linearity, caused by a multitude of feedback loops. These characteristics are also typical for SoS, which, on formal grounds, puts into question resilience analysis techniques based on mathematical analysis and statistics.

From a more practical standpoint, several characterizations have been given of complexity in real-world systems, which are very relevant also for SoS and resilience. The Cynefin framework (Snowden & Boone, 2007; Cavallo & Ireland, 2014) characterizes complex contexts as lacking “right” answers and having many unknown unknowns, which calls for an approach based on probing, sensing, and then responding, with increasing levels of interaction and communication. Even more difficult situations are dubbed chaotic, which probably captures well what organizations face when dealing with serious disruptions. There, no clear cause-effect-relationships can be derived and many things are unknowable, making immediate actions to see what works, combined with clear and direct communication, parts of the recommended strategy.

The environment faced by many SoS can be characterized as volatile, uncertain, complex, and ambiguous (VUCA) (Bennett & Lemoine, 2014). This calls for capabilities to enhance agility, information gathering, using experimentation to deal with complexity, and to reorganize to match the changing environment. Siemieniuch et al. (2015) characterize recovery from disruptions as a wicked problem (Rittel & Webber, 1973), a concept typical of large, societal systems where different stakeholders have disparate world views, and where it is hard to exhaustively characterize both the problem and potential solutions.

7 Conclusions

Transportation systems are becoming more complex, with many different and interrelated actors, and new technologies lead to a tighter integration with other sectors. This makes a system-of-systems (SoS) perspective increasingly relevant. The increasing interconnectedness also makes transportation more susceptibility to disturbances, which is further aggravated by contextual factors such as climate change and geopolitics. To deal with these uncertainties, increasing knowledge and awareness of resilience is needed, in particular in relation to SoS.

This report has presented technical results from a pre-study project at the intersection of SoS, resilience, and transportation. Three overall research questions were defined:

1. What is the state-of-the-art of SoS engineering for resilience?
2. What are the existing methods to analyze and quantify transport system resilience and how can they further develop to address emerging challenges?
3. What research gaps are there regarding transport SoS resilience, and what research topics should be prioritized in the coming years for building long-term resilience?

The remainder of this chapter summarizes the activities and results for each of these questions.

7.1 Systems-of-systems and resilience

The first research question addressed the state-of-the-art of SoS engineering for resilience. This was primarily investigated using an extensive systematic literature review (see Chapter 2). The review identified various modeling approaches for SoS resilience, and in particular a layered graph approach that includes macro, meso, micro, and spatial layers with interconnections between them. This model structure is beneficial for defining resilience measures, where disturbances occur at the lower levels and are then aggregated to characterize the effects in terms of reduced capabilities. The aggregation is also temporal, since both the duration and magnitude of a disturbance affect resilience. For resilience enhancement, various types of changes to the SoS are possible, both structurally (e.g., changing communication topology, types of constellations, or hardening of individual systems) and operationally (such as increasing redundancy or improving repair speed). The approaches available also depend on what assumptions are made about the knowledge of possible disturbances. Specified resilience assumes that disturbances are known and it is thus similar to risk analysis. General resilience does not assume any such knowledge and has to rely on more generic techniques for hardening the system.

7.2 Transportation system resilience

The second research question concerned existing methods to analyze and quantify transport system resilience and how they can further develop to address emerging challenges. This was addressed in three ways. The first was through analysis workshops with subject-matter experts (see Chapter 3). The analysis built on the layered models of SoS described previously, and identified specific macro-level capabilities, meso-level constellations, and micro-level actors for the transportation system. The analysis included not only actors directly involved in the primary transportation capabilities, but also the energy, communication, and computation system operators, and various authorities, who all play important roles in shaping the future transportation systems.

The second activity was to investigate specific methods and tools for resilience analysis of road networks (see Chapter 4). Many tools used today for planning infrastructure enhancements are based on equilibrium traffic flows, and brute-force methods are needed to systematically change key inputs to understand how perturbations propagate. This provides insights about sensitivity, capacity

constraints, and emergent vulnerabilities, which can inform specific SoS engineering measures to improve resilience. In addition, infrastructure analysis tools need to consider the intersection between transportation and other domains, such as energy supply.

Finally, an extensive catalogue of indicators relevant to transportation resilience was developed and organized in a classification framework (Chapter 5). The indicators were classified according to resilience phase, system layer, type, analysis method, required data and its availability, and to what types of disruptions they are relevant. Further, they were grouped into what parts of the SoS it relates to, such as transport infrastructure, operations, logistics, energy, digital connectivity, economic and environmental effects, etc.

7.3 Knowledge gaps and future research

The third research question concerned what knowledge gaps exist regarding transport SoS resilience, and what research topics should be prioritized in the coming years for building long-term resilience. The findings of the study point in several directions worthy of further attention, including:

- *General vs. specified resilience*. The bulk of the existing literature on SoS and resilience deals with specified resilience but given the inherent lack of data on truly disruptive events, general resilience should be given more attention. With that said, knowledge of specific risks should, of course, be used when it is available, so methods that combine the two aspects are needed. However, from a research perspective, the need for improving the general resilience methods appears to be most pressing.
- *SoS design patterns*. To address general SoS resilience, it would be valuable to identify relevant design patterns (Axelsson, 2024). Such patterns would need to be expressed using SoS models, such as the layered graphs described in Figure 5, and should include specific capabilities for enhancing resilience. These can relate to different resilience phases of preparation, absorption, recovery, and adaptation, and would need to be dynamic.
- *SoS analysis methods*. There is a potential to improve the analysis methods for resilience. Methods are needed on all layers of the proposed SoS model, as well as to link indicators on different layers. However, the methods need to be realistic and not ignore difficulties regarding uncertainties and the availability of data.
- *Cost-benefit trade-offs*. A particularly challenging aspect of resilience is how to motivate investments whose value cannot be quantified, given the uncertainty of disruptions. This is by no means specific to SoS and has been described previously as wicked problems (Rittel & Webber, 1973). For societal systems, it becomes in the end a political question rather than a scientific or engineering one. What can be done, though, is to improve methods in order to provide a more solid decision basis for those political decisions.
- *Holistic thinking*. Transportation applications highlight the need for holistic thinking, where traditional domain boundaries are dissolving. A future transportation system with increased electrification requires an analysis of the interactions between two societal systems, which are both SoS in their own right and at the same time together form another SoS. It makes it evident that SoS cannot be approached by the same systems engineering mindset that is used for integrated products, and new methods for SoS thinking need to be explored (Axelsson, 2026).

As a final remark, it should be noted that progress in the above research directions would also benefit other aspects of SoS than resilience. The need for holistic modeling, analysis, design patterns, and cost-benefit trade-offs exists at all levels, also for many other quality attributes than resilience.

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