

Chapter 15

Assessing the Resilience of the Current and Future Transportation System



Tudor Mocanu , Sophie Nägele , and Moritz Bergfeld

Abstract The resilience of the transport system has been extensively researched in the past decades. Research has so far focused mainly on natural hazards as the main threat to the system. Current and future developments in the transport sector and beyond like automatization, digitalization, transition towards renewable energies and climate change will likely increase the complexity of the transport system and pose new challenges to ensuring the resilience of the system. Amidst these developments, the role of individual behaviour during disruptions will be crucial and needs to be better understood. In spite of the wealth of previous research on resilience, so far, no standard methodology for the assessment of the resilience at system-level could be established. In order to provide a roadmap towards such a methodology we discuss the intended functionality, structure and components of the transport system and propose several approaches on how to operationalize resilience metrics in a model-based framework.

Keywords Transportation · Transportation system · Transportation resilience · Digitalization · Sector coupling · Climate change · Travellers' behaviour · Assessment framework

15.1 Introduction

In light of the goal of many countries to reduce greenhouse gas emissions and reach carbon neutrality, the transportation system will have to undergo a comprehensive transformation. One of the key factors in achieving carbon neutrality in the transport sector is a shift towards direct electrification, i.e. the increased usage of electricity as energy source at the expense of fossil fuels (e.g. International Council on Clean Transportation 2020). The increased electrification will add new components to, but also new opportunities and challenges for the transport system, such as the charging infrastructure, vehicle-to-grid (V2G) systems and the sector coupling. This increases

T. Mocanu (✉) · S. Nägele · M. Bergfeld
Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany
e-mail: Tudor.Mocanu@dlr.de

© The Author(s) 2026
D. van Doren et al. (eds.), *Towards Energy System Resilience*, Ethics of Science and Technology Assessment 55, https://doi.org/10.1007/978-3-032-03187-7_15

the connection to and dependency from the energy system. In the context of the energy transition, this connection is becoming even more important.

In parallel with the energy transition of the transportation system, the trend towards digitalization and an increasingly intelligent transport system will also be one of the main drivers shaping the future of this sector. Digitalization will not only manifest itself in the context of autonomous driving, but will also enable new mobility services that largely rely on digital technologies (e.g. shared mobility services such as ride-or carsharing) or improve existing services by digital traveller information systems (Bieser and Kriukelyte 2021).

The above-mentioned trends and developments will increase the complexity of the transport system and the interdependencies between its components and thus increase the importance of analysing the resilience of such a system. Although studying the resilience of the transport system is by no means a new topic and has been conducted extensively in the past couple of decades, the forthcoming transformation of the transportation system might pose some novel research questions that have not been adequately considered so far.

The aim of this chapter is to provide an overview of the current state of research on transportation resilience and transportation resilience assessment and monitoring methods. We will hereby focus on aspects related to electrification, energy transition and digitalization. We do not attempt to achieve an exhaustive review of all previous transportation resilience studies, but rather to offer a selection of papers and studies as starting point for readers interested in a more in-depth research. In light of the present knowledge regarding the resilience of the transport system and its transformation and future challenges we will also discuss the necessity for a more comprehensive assessment framework. Therefore, we will also address some of the key aspects and requirements of such a framework. Furthermore, we also attempt to identify research gaps and possible directions for future research in light of the above-mentioned trends.

This chapter is structured as followed: First we give an overview of the literature on transportation resilience research, starting with a generic definition and comprehensive review studies and continuing with a more detailed presentation of selected topics of special relevance. We then present a roadmap towards establishing a framework for transport system resilience assessment. Finally, we also identify the most relevant research topics in the context of the energy transition and digitalization and map out potential directions for future research in this field.

15.2 Previous Research on Transportation Resilience

15.2.1 *Definition of Resilience in the Transport Sector: A Diverse Field*

Research on the concept of resilience spans across a highly diverse set of disciplines and topics. Consequently, there have already been quite a few systematic reviews of how to define transportation resilience (see e.g. Zhou et al. 2019; Wan et al. 2018). The wealth of research so far has produced a great variety of different transportation resilience definitions and has made it difficult to find a generally accepted definition of resilience in the transport field (Wan et al. 2018). The latter authors wrote a comprehensive transportation resilience definition review and precisely describe the main differences between transportation resilience definitions. They show that different definitions have different scopes. While some focus on the whole transportation system, others focus only on specific aspects. Some describe resilience as the ability to return to a specific functioning, while others define it as a capability of the system itself. In their comprehensive review, (Wan et al. 2018) summarize transportation resilience as the ability to absorb disturbances, maintain the system functionality and recover to a certain level of service after being affected by disruptions (Wan et al. 2018).

We will subsequently use this rather generic definition of resilience as a starting point to explore several aspects in-depth in the following sections. Furthermore, in Sect. 3.2 we will give some insights into how these concepts can be operationalized and implemented.

15.2.2 *Comprehensive Literature Review Studies*

Previous research has investigated transportation resilience from different perspectives. For example, (Wan et al. 2018) parse the existing literature by reviewing both objectives and research methods. They show that resilience has gained an increased popularity in the transportation research field in recent years, but relatively late compared to other fields. The review shows that natural hazards are predominantly investigated as a source of disturbance and ports as research objects. The dominant research method in this field is mathematical modelling (57.3% of the selected works). This method is followed by simulation (more than one third) and conceptual works such as definitions (less than one fifth), surveys (about 10%) and case studies (about 5%). Furthermore, the authors show that 70.5% of the research is of quantitative nature and only 29.5% is qualitative (Wan et al. 2018).

Zhou et al. (2019) provide a comprehensive literature review focusing on metrics and mathematical models to measure resilience and strategies to enhance resilience. The authors show that resilience indicators can be divided into topological, attributes-based, and performance-based metrics. Measurement approaches can be divided into

optimization, topological, simulation, probability theory, fuzzy logic, and data-driven models. The authors argue that the enhancement of resilience is interrelated to the previous methods, however, most of the studies only focus on one method and on only one phase of the resilience assessment (most of the time operationalized by the cycle of disaster: mitigation, preparedness, response, recovery). What is missing from the findings is research about the role of the human being in the recovery phase and the societal perspective of resilience in general, as most of the research focuses on technology. Furthermore, the authors describe another problem: previous methods can hardly be applied to complex (interdependent) transportation systems (Zhou et al. 2019).

Due to the wealth of literature other researchers focus on only one aspect of the transportation system. For example, Bešinović (2020) investigates the railway transport system resilience. She emphasizes that railway transport demand is rising, which will be followed by more congestion and more complex, interdependent systems. Due to this development as well as system failures and climate change, she expects an increasing number of disruptions. She emphasizes the need for a field specific definition of resilience and for a widely accepted method to quantify impacts of disruptions and the evolution of system performance (Bešinović 2020).

Other researchers focus on more holistic approaches. Tamvakis and Xenidis (2012) investigate key variables for a holistic design of transportation systems including resilience. They highlight the need for resilience engineering, which ensures a certain minimum operation level in case of sudden disturbances and a quick recovery potential. They also present first steps towards a new approach to assess transportation systems resilience (Tamvakis and Xenidis 2012).

15.2.3 Threats to the Transportation System

A large part of transportation resilience research focuses on various threats to the transportation system. Dominant threats are natural hazards. Among the different kinds of natural hazards investigated are hurricanes (see e.g. Yin et al. 2014; Wu et al. 2012), typhoons (Wang and Taylor 2015), or winter roads (Nævestad et al. 2021). Wu et al. (2012) investigate evacuation logistics, and more specifically the activities and resources needed to reach a safe location during hurricanes Katrina and Rita. They found that evacuees most likely choose the homes of friends or relatives as shelter, take multiple cars and rely on experience and traffic conditions to choose an evacuation route. Yin et al. (2014) use a slightly different approach, employing an agent-based travel demand model system for hurricane evacuation simulations. Wang and Taylor (2015) investigate the impact of typhoons on human mobility patterns. Even though human mobility can be influenced by typhoons, the authors show that the power law still applies to human mobility patterns, which indicates that fundamental travel patterns are resilient. Nævestad et al. (2021) focus on a less dramatic natural hazard: winter roads in Norway. They investigate how heavy goods vehicle drivers adapt to winter roads and compare foreign and Norwegian drivers. They show that

foreign drivers feel less safe on Norwegian winter roads and are more likely to have accidents compared to Norwegian drivers, who also feel more confident. In summary, natural hazards threaten transportation systems and the investigation of these aspects improves the knowledge on how to make the transportation system more resilient.

Other unexpected events such as industrial disputes or strikes have also been investigated to analyse the resilience of the railway system (van Exel and Rietveld 2009). The authors investigate rail users' behaviour before and after a national strike in the Netherlands. They analyse associations between traveller and trip characteristics as well as anticipated and actual reactions. The results show that 44% of those who wanted to travel by train on the day of the strike cancelled their trip, 24% used the car as a driver instead, 14% took another mode as passenger and 18% took the train on another day. Such results can help to adapt to strikes and enhance the resilience of a specific, affected transport system. Finally, pandemic situations have also been investigated in the light of the resilience of transportation systems (Teixeira et al. 2021). The authors investigate whether the Corona pandemic influenced the use of bike sharing. They show that bike sharing is an asset for the resilience of urban transport systems especially during a health crisis as they are perceived to be capable of preserving social distancing.

15.2.4 Data Sources and Analysis Methods

Another important part of transportation resilience research concentrates on the data and methods that can be used to investigate the resilience of a transport system. Examples for data sources are mobile phone data to track down individuals (Peak et al. 2018), GPS data from probe vehicles like taxis (Donovan and Work 2017), location-based service data from Baidu Map analysed by GIS and spatial flow analysis (Chen et al. 2020), or social media data (Roy et al. 2019). These different data sources are used to investigate human mobility during disruptions in order to provide insights and knowledge for transportation system planners to prepare for potential hazards.

Different methods to quantify transportation resilience have been applied, such as pace deviations during normal versus unusual events (Donovan and Work 2017) or path length analyses (Morelli and Cunha 2021). Since many different definitions of resilience exist, just as many different quantification approaches have been developed. Consequently, Bešinović (2020) argues that there is a need for an agreed quantification of the impact of disruptions. This further illustrates the current wealth of transportation resilience research.

15.2.5 Resilience in the Context of Individual Behaviour

Disruptions require people to make quick decisions and can also trigger anxiety and fear. The evaluation of the respective situation decisively influences the individual

ability to react adequately. Therefore, it is important to also investigate the effects of disruptive events on individuals.

One study investigates 15 destructive situations of five different kinds of natural disasters and their effects on mobility patterns before, during and afterwards (Wang and Taylor 2016). They show that mobility patterns are correlated during the different measurement points but not during very heavy events. This means that mobility patterns during normal state and disasters are somewhat related, but only up to a specific disruption threshold, after which the correlation declines. The authors emphasize the need for a deeper understanding of mobility during disasters to avoid negative effects for the population.

Marsden et al. (2020) emphasize the necessity to examine how the transport system and mobility patterns change when facing disruptive events. They investigate behavioural adaptations in reaction to disruptive events. The authors find seven coping strategies in response to three disruptive events, winter weather, flooding, and a bridge closure that were followed by road closures of several days to a few weeks: (1) Remoding: using a different mode of transport for at least the main leg of the trip; (2) Rerouting: taking a different route from that which was planned or would typically be taken; (3) Retiming: modifying the time at which a trip starts by either bringing it forward or pushing it back without altering where in the sequence of activities it occurs; (4) Rescheduling: changing when in the week a trip is made. This is distinct from retiming as the trip is moved in a sequence of activities; (5) Relocating: changing the destination of a journey such as shopping somewhere else; (6) Reallocating: passing over the responsibility for a journey to someone else (e.g. childcare pick up or caring trip); (7) Reducing: not conducting a trip at all but conducting the activity through ICT.

Another similar study by Parkes et al. (2016) shows that the most common behavioural responses as a reaction to overcrowding in public transport during the Olympic games in London 2012 were retiming and reducing journeys (33 and 32% of respondents respectively), compared to 19% rerouting and 14% remoding.

Zhu and Levinson (2010) find that the preference for driving a car was very strong after disruptions. Additionally, **travel experience** seems to be an important variable as new habits may emerge through experience. In another study about suburban train users, the authors identify coping mechanisms and aspects related to the decision-making process of suburban train passengers when service is interrupted or delayed (Adelé et al. 2019). They reveal that factors relating to the individual (e.g., **expertise**), the journey (e.g., **time constraints**) and also information (pre-trip or enroute communication of the disruption) affect the behaviour. They also show that travel behaviour is further influenced by **available transport services**, **car availability**, the situation in which the disruption occurs, perception of service recovery time, as well as the attitudes towards information services. For example, those with route expertise are more willing to wait, compared to those with no route expertise (van der Horst and Ettema 2005), or are more reluctant to use unknown routes (Chorus et al. 2006). If a car is available in the household, it is more likely to be used when a disaster happens (Adelé et al. 2019). Yet another study shows that **car access**, **travel time**, **travel cost**, **trip importance**, and **weather** influence whether someone will switch

from public transport to car due to a public transport disruption (Nguyen-Phuoc et al. 2018).

Finally, there are also differences between the modes of transportation in terms of their robustness during disruptions. For example, **walking and cycling can be seen as more robust** compared to motorized individual transport and longer trips are more vulnerable compared to shorter trips. This raises the point that the focus on motorized individual transport in resilience planning could actually worsen the transportation system vulnerabilities (Morelli and Cunha 2021).

15.2.6 Future Trends in the Transportation System

15.2.6.1 Resilience in the Context of Automatization, Digitalization and New Transportation Services

Johnsen and Kilskar (2020) investigate the effects of **automatization** on the resilience of transportation systems. They find that automatization itself might increase vulnerabilities, for example due to human attention failures or poor human machine interaction design. The authors emphasize that one key resilience factor of automated systems is being able to handle unexpected situations. Furthermore, automated systems also have to be resilient in order to increase the trust in such new technologies. The authors point out that if automated functions are not perceived as safe and therefore resilient in face of countless different situations, users will not be willing to use such functions (Johnsen and Kilskar 2020).

Buinevich and Vladyko (2019) investigate the effects of **digitalization** on the resilience of transportation systems. They show that one important aspect of digitalization in the transportation sector are wireless communication technologies for intelligent transportation system applications, which represent a new potential target for cyber-attacks. Any interruption of these systems might endanger the safety of e.g. passengers and trains since such communication technologies are employed to warn drivers about obstacles, systems failures, and other interruptions. The authors emphasize the need for cyber-resilient transportation systems.

Mitusch (2021) analyses the resilience of **new transportation services**, e.g. car or bike sharing. The author concludes that, because of the more flexible usage options of these new modes they are more resilient compared to collectively used modes of transport. However, the author emphasizes that, as most of these new services are running on electricity, they are dependent on a well-functioning electricity supply. Furthermore, he points out that the optimal utilization of a pool of vehicles may imply a reduction in the total number of required vehicles compared to individual vehicle ownership. In case of a disturbance this may cause a lack of available vehicles since the number of shared vehicles is optimized for normal conditions.

15.2.6.2 Resilience in the Context of Climate Change

Markolf et al. (2019) discuss the transportation system resilience in face of climate change. Our transportation system is built on historical climate observations, but climate change is making such assumptions obsolete. The authors differentiate between direct and indirect threats. Currently, research is focussing more on direct threats and the goal is to make the system more robust. However, the authors conclude that the indirect threats are just as important to consider, and robustness does not protect the transportation system. The authors emphasize the importance of expanding the scope towards flexibility and agility above robustness to make the transportation system more resilient in face of climate change (Markolf et al. 2019).

One important aspect of a sustainable and therefore of a resilient transportation system is congestion (Afrin and Yodo 2020). However, until now research has focused on capturing “typical” circumstances, meaning the “normal” mobility (Marsden et al. 2020). The authors highlight that this leads to an overestimation of the rigidity and invariability of individuals’ travel patterns. They emphasize how important it is to close this research gap, especially in face of climate change. Such research could lead to a better understanding of how flexible mobility patterns really are.

Adaptation strategies can also be observed in actions of transportation service and infrastructure companies. For example, the German national railway infrastructure operator, DB InfraGO (formerly DB Netz), has implemented a natural hazard strategy to adapt to the effects of climate change. They analyse dependencies and relations between different effects, economical aspects and derive the need for action (Meßenzehl 2019). However, due to climate change, weather will become less predictable and more variant, which will in turn lead to less accurate forecasts and forewarnings (Mitusch 2021).

15.2.6.3 Resilience in the Context of Energy Transition and Electrification of the Transportation System

The electrification of the transport sector and therefore the coupling to the energy sector brings various challenges and opportunities in relation to the resilience of both sectors. Brown and Soni (2019) survey members of the U.S. Department of Energy’s Electricity Advisory Committee to assess the market potential and challenges from the integration of vehicles in the electricity grid. The authors examine the survey results in combination with a literature review, current policies and the ecosystem of stakeholders. They find that grid-to-vehicle integration is the most valuable mode. Furthermore, the management of transport and energy as complementary sectors could uncover the benefits for grid resilience. A coordinated policy approach involving multiple sectors and infrastructures can support complementarities across sectors and significantly contribute to network resilience. The main barriers to grid-integrated EVs are operational and administrative in nature (Brown and Soni 2019).

This knowledge raises the question of how electric vehicles could be integrated and utilized into the grid system during emergency events to enhance resilience. Hussain et al. (2020) investigate microgrids and energy management during emergency cases. Within their research they develop a communication-based energy management system for emergency cases. This approach provides interoperability and plug and play solutions. Because EVs are spatially distributed and portable storage systems, they are of high value in emergency situations. The energy stored in the vehicles can be used until help arrives. To enable different energy system components to work together in such cases, standards must be expanded and combined with smart grid or smart city concepts (Hussain et al. 2020).

If disasters can be predicted like extreme weather events, the benefits on resilience from electric vehicles can be enhanced. Roudbari et al. (2021) investigate the opportunities to enhance resilience by rescheduling resources and charging/discharging patterns before and during extreme weather events. The effectiveness could be demonstrated through several case studies.

On the other side it is necessary to consider the resilience of electric vehicles when it comes to emergency situations. Hussain and Musilek (2022) analyse existing literature to discuss the use of electric vehicles as resilience resource and the resilience of electric vehicles themselves. They propose different strategies and techniques to enhance the resilience of electric vehicles during disasters. Prior to an event, resilience can be increased by including storage capacity in the charging infrastructure or building renewably powered off grid charging stations. During disruptions the allocation of power to EVs and along evacuation routes has an impact on mobility and possible evacuation options. However, in addition to the V2G issue (see above), there are other issues that need to be addressed, such as coordination among stakeholders, standardization, installation of charging stations, and shaping public policy to include electric vehicles (Hussain and Musilek 2022).

15.3 Towards a Framework for the Assessment of the Transportation System Resilience

After having presented the main directions of research in the context of transport system resilience we now turn our attention to the question of how the resilience of this system can be assessed and quantified. Unsurprisingly, there is no readily available state-of-the-art or even state-of-practice methodology for this task, since assessing the resilience of the entire transport system has not been so far up on the agenda of policy makers and practitioners so far. However, as previously discussed in Sect. 15.1, the impending transformation of the transport system and the associated new challenges will render this assessment considerably more pertinent in the future.

The following sections will present several fundamental aspects that need to be considered in developing a roadmap towards a comprehensive and future-proof

resilience assessment framework. We start by undertaking a more detailed examination of the transport system, followed by an analysis of conceptual transport resilience indicators and how they can be operationalized. Finally, we present a possible implementation of resilience assessment using model-based analyses.

15.3.1 Scope and Boundaries of the Transportation System

In order to assess the resilience of any system, it is imperative to have a clear understanding of the intended system functionality, system components and boundaries. The transportation system is surprisingly difficult to describe in unambiguous and comprehensive terms. For instance, one definition refers to the transport system rather generically as a set of multiple elements that interact with each other and produce both a certain demand for travel as well as the transportation supply (services) required to meet this demand (Cascetta 2009).

A system can first be described in terms of its intended functionality. In a nutshell, the purpose of the transport system is to ensure the mobility of persons and goods (and according to some wider definitions also of information) at an acceptable level of service and costs. Several implications for resilience analyses derive from this high-level definition. Firstly, it is important to consider both the supply and the demand and how well they match together. Secondly, the performance of the system should be assessed from the perspective of the end users, as there is no universal or objective definition of what are “acceptable” levels of service or costs associated with travel. Furthermore, demand for (passenger) transport has traditionally been considered as being derived from the necessity of carrying out activities at other destinations (Mokhtarian and Salomon 2001). An interesting question that arises from this consideration is whether or not the provision of alternative destinations, locations or substitutes for the originally planned activities in case of disruptions still falls within the boundaries of the transport system. A pertinent example for this discussion was the sudden increase in working from home in response to the onset of the COVID-19 pandemic. This drastically reduced the demand for commuting while still enabling the originally planned activities (working) to be carried out. While such a reaction is a clear indication of resilience, we consider that in this case it was not the transportation system itself but actually the “societal system” as a whole that has shown resilience, since enabling people to work is not the primary function of the transportation system. Nevertheless, this example demonstrates the extent to which the transportation system is integrated within other, broader systems.

Another way of describing the transportation system that is useful for resilience analyses is to consider its components and structure. (Tamvakis and Xenidis 2012) propose a two-layered definition of the transportation system where the inner layer consists of six physical components (infrastructure, vehicles, equipment, power

systems, fuel, communication systems) and the outer layer consists of external stakeholders (e.g. government, general public, financial community etc.). This is a comprehensive definition that appears to include several relevant aspects in addition to the most obvious core elements (e.g. infrastructure and vehicles).

For the purpose of resilience analyses it might be more beneficial to expand the system definition proposed by Tamvakis and Xenidis (2012) by structuring the transportation system and its components according to different kinds of vulnerabilities and possible kinds of reactions with respect to that. For example, let's consider the physical component "Infrastructure". This component has several vulnerabilities, one example being that roads can be blocked by heavy snowfall. The factors and sub-systems that influence the mitigation and adaptation reactions are equally important. In our example this could be how well-organized the snow plough operation is and how quickly the original functionality of the system component (e.g. a clean, snow-free road) can be restored. This part of the transportation system could be termed as "recovery support components". The concept can be applied to any of the key system components and its existence and performance is crucial in the assessment of the system resilience. As with the aspect of providing alternative destinations discussed above, the outer boundary of the transportation system cannot easily be defined and it is debatable up to which point these recovery support components should still be included in the definition. For the purposes of resilience system analyses, however, they should at least be considered.

Based on these considerations we propose an updated, end user-focused description and structure of the transportation system well suited for resilience analyses, which includes the following components (Fig. 15.1):

- Core:
 - *Individuals and end users*: the actual "beneficiaries" of the transportation system that need to get from A to B

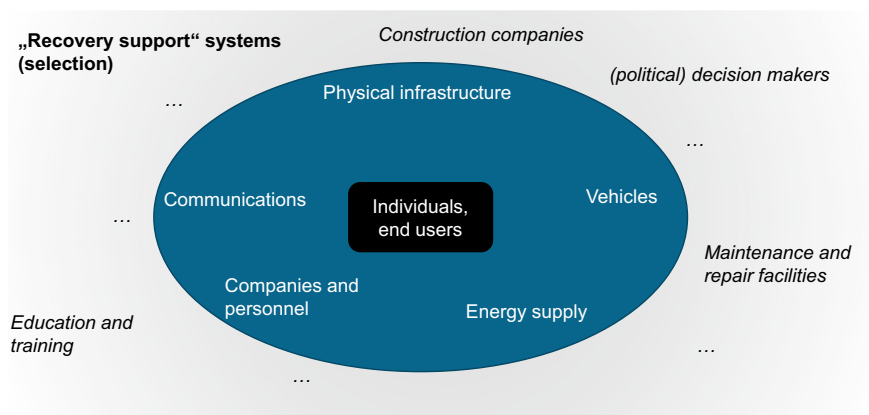


Fig. 15.1 Updated transportation system structuring for resilience analyses

- Key system components:
 - *Physical infrastructure*: the different transport networks (road, rail, waterways, stations, terminals, ports etc.)
 - *Vehicles*: the moving vessels (cars, trains, airplanes etc.)
 - *Companies and personnel*: the providers of transportation services (logistics companies, public transport companies, drivers etc.)
 - *Energy supply*: petrol stations, power plant operators, grid operators etc.
 - *Communications*: Mobile networks, 5G providers, internet platforms etc.
- Recovery support:
 - all systems (technical, procedures, companies, institutions) that act towards restoring the full functionality of any of the key system components in case of disruptions (e.g. construction companies repairing damage to the physical infrastructure or repair facilities repairing damage to vehicles etc.).

15.3.2 Operationalization of Resilience Concepts

With a better understanding of the purpose, scope and structure of the transport system we can now turn our attention to how its resilience can be quantified and assessed. Implementing the generic definition of resilience given in Sect. 2.1 into a framework for quantitative analyses is not straightforward. A useful, generic concept is the so-called “resilience triangle” that was originally proposed by Bruneau et al. (2003) for the evaluation of infrastructure resilience. This simplified conceptual model, as illustrated in Fig. 15.2, considers the time-varying performance of the (transportation) system before, during and after a disruptive event. In the immediate aftermath of the disruption (t_0), the performance decays. The robustness of the system and its redundancies determine the extent of the decay. After the minimum of performance has been reached (t_1), the system enters the recovery phase where the functionality is gradually restored. The hashed area in Fig. 15.2 indicates the impact of the disruption on the system. The smaller this area is, the more resilient the system is. This can be achieved by minimizing either the initial performance decay (through robustness and redundancy), the time to full performance recovery (through resourcefulness and rapidity), or both.

The next question is, then, what constitutes an appropriate measure for the overall performance of the transport system (the y-axis of the conceptual model in Fig. 15.2). Various metrics have been used both at sub-system levels (i.e. to assess the performance of individual components of the transportation system) and for the overall system (Zhou et al. 2019). For a system-wide performance analysis we must return to the definition of the intended system functionality given in Sect. 3.1. Since the purpose of the transportation system is to provide accessibility at minimal cost, it is precisely this metric which should form the basis for the resilience assessment.

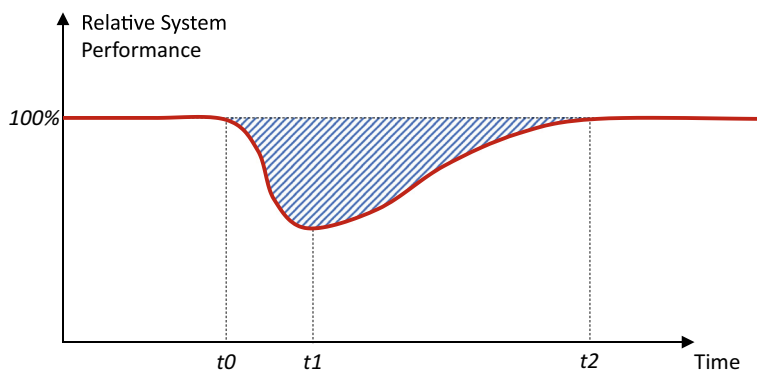


Fig. 15.2 Two phases of resilience measurement, according to Zhou et al. (2019)

This can be implemented into two relatively straight-forward metrics based on the underlying travel demand:

1. Percentage of serviced demand, i.e. ideal performance of the system is achieved when all trips and movement can be carried out as originally planned, in spite of any disruptions.
2. Impedance index, i.e. a comparison of the current total impedance in the network with a best-case (undisrupted) scenario (see e.g. Twumasi-Boakyee and Sobanjo 2018). The most relevant impedance metric is travel time, but measures of generalized cost including monetary and/or other types of impedances are also possible.

For sub-components of the transportation system, other indicators are required. For example, access and availability of charging infrastructure for battery-powered electric vehicles is an indicator worth considering in the light of electrification of transport. Since the charging infrastructure depends on the power grid cross-sectoral effects must be considered.

It should be noted here that this operationalization of resilience analysis is an event-based assessment framework, i.e. it requires consideration of possible disruptions to the system. This is a useful approach in many cases, but there are also some drawbacks to consider here. Firstly, the assessment results will depend heavily on the exact disruption(s) considered so care should be taken when selecting the stressors. Ideally, for a comprehensive system analysis a wide-ranging set of disruptions should be investigated in order to avoid selection bias. Furthermore, when assessing future system configurations that greatly differ from the current one (e.g. a fully automatized and digitalized transport system as indicated in Sect. 2.6.1), it might not be so obvious at a first glance which disruptions are the most relevant. In some cases, resilience-enhancing measures for one disruption might also increase the vulnerability to other disruptions (e.g. digitalization might help in natural catastrophes but will also increase vulnerability to a hacker attack). Therefore, the event-based assessment could be supplemented by a structural one.

Structural indicators are generally employed to describe a system's robustness and redundancy. In transportation system analyses, such indicators have been developed mainly to describe the topology of (road) networks using graph theory concepts and include metrics such as the network diameter, average shortest path, average node degree, size of giant component etc. (Zhou et al. 2019). Another relevant structural indicator might be the total excess capacity, i.e. a network-wide aggregation of the difference between the maximum capacity of each link and the regular (undisturbed) traffic volumes. However, such indicators are difficult to apply in the context of multi-modal, system-wide analyses investigating disruptions more complex than singular link outages in simple networks.

One promising theoretical approach comes from microeconomics and has been employed in transportation in the context of choice modelling. The expected maximum utility, or logsum term, is a measure of consumer surplus in choice situations (see e.g. Jong et al. 2005). The greater the number of alternatives included in the choice set, the higher the logsum will be. From the perspective of the end user (e.g. a traveller), the transportation system can also be seen as a series of choices (e.g. destination, travel mode, route etc.). It should thus be possible to calculate logsums for each choice situation and aggregate them. By comparing the (aggregated) logsum to the actual utility of the (modelled) best or preferred alternative, it appears theoretically possible to evaluate the redundancy of the system. A more redundant system will have a higher difference between the logsum term and the best singular alternative. However, further research is required to operationalize this concept.

15.3.3 Model-Based Analyses for Resilience Assessment

Building upon the aspects discussed in Sects. 3.1 and 3.2, it becomes clear that establishing a framework for the comprehensive assessment of the resilience of current and future transport system is not a trivial task. This framework should include all relevant parts of the system (see Fig. 15.1) and enable the time-dependent, dynamic assessment of their performance. Based on this, indicators for both the event-based and the structural assessment discussed in Sect. 3.2 should be derived. In the following we will attempt to lay out a roadmap towards establishing such a framework.

Firstly, a proper model-based tooling should be developed. The starting point for this tool could be provided by already existing transport models and simulations. With such models it is already possible to compute the system performance metrics for any given timestep in Fig. 15.2. Conventional transport models usually consider both transport supply (e.g. the capacity and other characteristics of the road network, public transport scheduling etc.) and its impact on travel demand. If changes are made on the supply side, e.g. by reducing the capacities or removing certain links from the network altogether, then this could have an impact on demand at various steps in the transport model. Depending on the type of model and its sensitivity, such changes could be seen in terms of route choice and flow re-routing, mode choice, destination

choice etc. By comparing the model results from disruption and undisrupted scenarios it is possible to calculate the impedance indices presented in Sect. 3.2. If the point in time with the lowest system performance (t_1) is selected and compared to the undisrupted system performance, the results could also be interpreted as an analysis of the system's robustness.

In more complex, so called "activity-based" travel demand models it is also possible to model changes in the activity patterns of individuals as a result of enhanced or degraded accessibility and thus also directly calculate the percentage of serviced demand. To assess future developments and cross-sectoral effects it may also be necessary to build interfaces between specialized models. Since the spatial and temporal resolution of different models might be very different a robust methodology needs to be established. Models with a higher temporal resolution might use a slice of temporal data from models with a lower temporal resolution. An interpolation methodology, as described later on, might help to build a sufficient interface. However, care should be taken when employing the models for such purposes because most of them have originally been developed and validated for long-term, strategic modelling.

The second step in the development of the model-based tooling should be to move from a static to a dynamic approach that is able to consider time-varying aspects before, during and after disruptions. Several approaches could make this possible. The first one is by employing dynamic simulations instead of conventional, static travel demand models. Dynamic simulations consider an explicit time axis and model the changes in the state of subjects or agents during the simulated period. Such simulations have been developed with the main focus on increasing the accuracy of the network assignment step, since there are obvious benefits in considering the dynamics of traffic flows and queues in a network. However, even in these dynamic simulations the travel demand (deriving from trip generation, destination, mode and time of day choice) is static and is not dynamically re-evaluated during the simulation. Understanding e.g. how travellers alter their activity plans spontaneously during a disruption is an open research question that warrants further investigation.

In transport models, the typical simulation period is one day (24 h), although there are also model implementations of week-long simulations (see e.g. Ordonez Medina et al. 2012). Depending on the disruptions to the transport system considered, it might be necessary to greatly expand this timeframe. This is especially relevant in the context of damages to the transport infrastructure, since repairing them could take months or even years. Performing continuous simulations for such extended periods of time is obviously not feasible. Instead, another approach could be to run multiple static models for several discrete points in time and then interpolate the results in between. This approximation would greatly simplify the modelling process and achieve an optimal trade-off between accuracy and computational efficiency by selecting the appropriate time intervals between the discrete simulations.

In both of the approaches mentioned above, it is important to also include the performance and behaviour of the relevant "recovery support" components of the transportation system (see Fig. 15.1). This goes beyond the scope of traditional transport models so new approaches will need to be developed for this purpose.

One obvious approach could be to make assumptions regarding the recovery support systems based on their observed performance during previous disturbances and stress situations. This simple approach could work well enough when there is sufficient historical data to base the assumptions on and when the interactions between different systems are negligible. For example, if a bridge has been destroyed by an extreme weather event, then the time required for reconstruction could be estimated from previous experience with such occurrences. However, if the construction companies (as an example of “recovery support” systems) are themselves affected by other disruptions, e.g. shortage of materials due to unavailable supply lines or budgetary and manpower constraints, then their performance might differ substantially from previous observations. Furthermore, the performance of recovery support actions for future technologies cannot be derived from historical data. This is illustrated by the example of electrification of transportation, where vehicles rely on electric energy, which is a different kind of infrastructure. Another example is autonomous driving, which could have a huge impact on travel patterns and vehicle movements. In these cases, it appears necessary to explicitly model the behaviour of the recovery support agents, e.g. by using (simplified) agent-based models or system dynamics models (Li et al. 2020).

Such a model-based tool for resilience analysis could primarily be used to assess the performance of the system by selecting relevant disruption scenarios and stress cases, simulating and analysing the results. By identifying those system features over which planners have an active influence on, the tooling can then also be used for design purposes. By finally running multiple simulations with different design parameters and options, it should be possible to identify some form of optimal system setup that maximizes resilience.

Figure 15.3 summarizes the proposed model-based resilience assessment framework. Starting from already existing transport models and simulations, an enhanced stress case evaluation tool will have to be established according the guidelines presented above. The utilization of this tool for the assessment of relevant stress cases will enable planners to monitor and better consider aspects of resilience when designing the future transportation system.

15.4 Conclusion

Research on the resilience of the transportation system has been conducted intensively during the last decades. There has been a specific focus on natural hazards and evacuations, but resilience has also been investigated from other perspectives. Latest developments in automatization, digitalization in the transport and energy transition and climate change have led to new research topics in the transport sector concerning resilience. Furthermore, these aspects are related to the individuals’ behaviour, which is also highly relevant in the context of resilience.

While there is a wealth of research on current and future threats to the transportation system, up until now only a very limited focus has been placed on developing

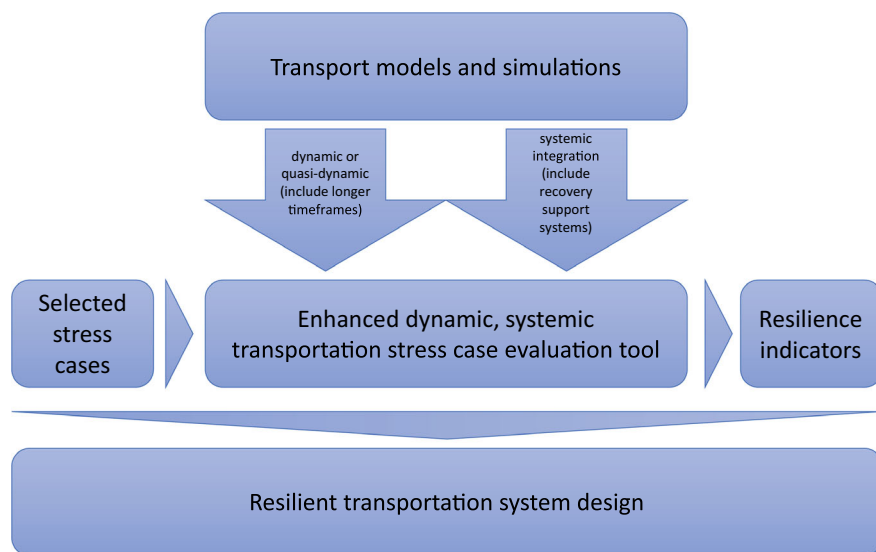


Fig. 15.3 Model-based resilience assessment framework

instruments and frameworks that allow planners and decision-makers to assess the resilience of the transportation system as a whole. Ideally, a comprehensive assessment framework should enable decision-makers to quantify both the costs and the benefits of a resilient transportation systems and take system design-related decisions accordingly.

This chapter has presented a vision of what such an integrated and comprehensive framework could look like in the future. For this vision to become reality and state-of-practice, research must now focus on developing practical and easily implementable tools that consider both short and long-term impacts on all resilience-related aspects of the transportation system, including the recovery support systems. The most obvious starting point in this endeavour are currently existing transport models and simulations, which can already be implemented to investigate the robustness and redundancy of several important parts of the transportation system, such as the transport networks. This should at least allow us to quickly identify the main vulnerabilities in our current system. Finding a quick solution for these vulnerabilities will, however, not be so straight-forward, especially in view of the often limited resources (financial, but also e.g. in terms of space in dense urban areas or shortage of skilled labour force available for construction work etc.) to expand our transportation systems. This will require an informed prioritization of policy interventions and optimal allocation of resources, for which a comprehensive resilience assessment framework, as proposed in this chapter, is an indispensable prerequisite.

References

- Adelé, S., Tréfond-Alexandre, S., Dionisio, C., Hoyau, P.-A.: Exploring the behavior of suburban train users in the event of disruptions. *Transp. Res. Part F Traffic Psychol. Behav.* **65**, 344–362 (2019). <https://doi.org/10.1016/j.trf.2019.08.009>
- Afrin, T., Yodo, N.: A survey of road traffic congestion measures towards a sustainable and resilient transportation system. *Sustainability* **12**(11), 4660 (2020). <https://doi.org/10.3390/su12114660>
- Bešinović, N.: Resilience in railway transport systems: a literature review and research agenda. *Transp. Rev.* **40**(4), 457–478 (2020). <https://doi.org/10.1080/01441647.2020.1728419>
- Bieser, J.C.T., Kriukelyte, E.: The digitalization of passenger transport. Technologies, applications and potential implications for greenhouse gas emissions. Department of Sustainable Development, Environmental Science and Engineering (SEED). Stockholm, Sweden (2021). <https://urn.kb.se/resolve?urn=urn%3Aanbn%3Ase%3Aakth%3Adiva-305425>
- Brown, M.A., Soni, A.: Expert perceptions of enhancing grid resilience with electric vehicles in the United States. *Energy Res. Soc. Sci.* **57**, 101241 (2019). <https://doi.org/10.1016/j.erss.2019.101241>
- Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., et al.: A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* **19**(4), 733–752 (2003). <https://doi.org/10.1193/1.1623497>
- Buinevich, M., Vladyko, A.: Forecasting issues of wireless communication networks' cyber resilience for an intelligent transportation system: an overview of cyber attacks. *Information* **10**(1), 27 (2019). <https://doi.org/10.3390/info10010027>
- Cascetta, E.: *Transportation Systems Analysis*, vol. 29. Springer US, Boston, MA (2009)
- Chen, Z., Gong, Z., Yang, S., Ma, Q., Kan, C.: Impact of extreme weather events on urban human flow: a perspective from location-based service data. *Comput. Environ. Urban Syst.* **83**, 101520 (2020). <https://doi.org/10.1016/j.compenvurbsys.2020.101520>
- Chorus, C.G., Molin, E.J.E., van Wee, B.: Use and effects of Advanced Traveller Information Services (ATIS): a review of the literature. *Transp. Rev.* **26**(2), 127–149 (2006). <https://doi.org/10.1080/01441640500333677>
- Donovan, B., Work, D.B.: Empirically quantifying city-scale transportation system resilience to extreme events. *Transp. Res. Part C Emerg. Technol.* **79**, 333–346 (2017). <https://doi.org/10.1016/j.trc.2017.03.002>
- Hussain, A., Musilek, P.: Resilience enhancement strategies for and through electric vehicles. *Sustain. Cities Soc.* **80**, 103788 (2022). <https://doi.org/10.1016/j.scs.2022.103788>
- Hussain, S.M.S., Aftab, M.A., Ali, I., Ustun, T.S.: IEC 61850 based energy management system using plug-in electric vehicles and distributed generators during emergencies. *Int. J. Electr. Power Energy Syst.* **119**, 105873 (2020). <https://doi.org/10.1016/j.ijepes.2020.105873>
- International Council on Clean Transportation: Vision 2050: a strategy to decarbonize the global transport sector by mid-century (2020). https://theicct.org/wp-content/uploads/2021/06/ICCT_Vision2050_sept2020.pdf. Accessed 28 Oct 2024
- Johnsen, S.O., Kilskar, S.S.: A review of resilience in autonomous transport to improve safety and security. In: Baraldi, P., Di Maio, F., Zio, E. (eds.) *Proceedings of the 30th European Safety and Reliability Conference and 15th Probabilistic Safety Assessment and Management Conference. Proceedings of the 29th European Safety and Reliability Conference (ESREL)*, 01.11.2020 - 05.11.2020, pp. 5059–5066. Research Publishing Services, Singapore (2020)
- de Jong, G., Pieters, M., Daly, A., Graafland-Essers, I., Kroes, E., Koopmans, C.: Using the logsum as an evaluation measure: literature and case study. RAND Corporation, Santa Monica, CA (2005). https://www.rand.org/pubs/working_papers/WR275.html
- Li, G., Kou, C., Wang, Y., Yang, H.: System dynamics modelling for improving urban resilience in Beijing, China. *Resour. Conserv. Recycl.* **161**, 104954 (2020). <https://doi.org/10.1016/j.resconrec.2020.104954>

- Markolf, S.A., Hoehne, C., Fraser, A., Chester, M.V., Underwood, B.S.: Transportation resilience to climate change and extreme weather events – beyond risk and robustness. *Transp. Policy* **74**, 174–186 (2019). <https://doi.org/10.1016/j.tranpol.2018.11.003>
- Marsden, G., Anable, J., Chatterton, T., Docherty, I., Faulconbridge, J., Murray, L., et al.: Studying disruptive events: Innovations in behaviour, opportunities for lower carbon transport policy? *Transp. Policy* **94**, 89–101 (2020). <https://doi.org/10.1016/j.tranpol.2020.04.008>
- Meßenzehl, K.: Das Naturgefahrenmanagement der DB Netz AG. Vorbereitung auf den Klimawandel. *Deine Bahn* **47**, 16–22 (2019)
- Mitusch, K.: Resilienz von Verkehrssystemen unter besonderer Berücksichtigung des Klimawandels (2021). <https://www.forschungsinformationssystem.de/servlet/is/543583/>. Accessed 31 Oct 2024
- Mokhtarian, P.L., Salomon, I.: How derived is the demand for travel? Some conceptual and measurement considerations. *Transp. Res. Part A Policy Pract.* **35**(8), 695–719 (2001). [https://doi.org/10.1016/S0965-8564\(00\)00013-6](https://doi.org/10.1016/S0965-8564(00)00013-6)
- Morelli, A.B., Cunha, A.L.: Measuring urban road network vulnerability to extreme events: an application for urban floods. *Transp. Res. Part D Transp. Environ.* **93**, 102770 (2021). <https://doi.org/10.1016/j.trd.2021.102770>
- Nævestad, T.-O., Sagberg, F., Levlin, G., Bjørnskau, T.: Competence, equipment and behavioural adaptation on Norwegian winter roads: a comparison of foreign and Norwegian HGV drivers. *Transp. Res. Part F Traffic Psychol. Behav.* **77**, 257–273 (2021). <https://doi.org/10.1016/j.trf.2021.01.004>
- Nguyen-Phuoc, D.Q., Currie, G., De Gruyter, C., Young, W.: How do public transport users adjust their travel behaviour if public transport ceases? A qualitative study. *Transp. Res. Part F Traffic Psychol. Behav.* **54**, 1–14 (2018). <https://doi.org/10.1016/j.trf.2018.01.009>
- Ordóñez Medina, S.A., Erath, A., Axhausen, K.W.: Simulating urban transport for a week time horizon (2012)
- Parkes, S.D., Jopson, A., Marsden, G.: Understanding travel behaviour change during mega-events: lessons from the London 2012 Games. *Transp. Res. Part A Policy Pract.* **92**, 104–119 (2016). <https://doi.org/10.1016/j.tra.2016.07.006>
- Peak, C.M., Wesolowski, A., zu Erbach-Schoenberg, E., Tatem, A.J., Wetter, E., Lu, X., et al.: Population mobility reductions associated with travel restrictions during the Ebola epidemic in Sierra Leone: use of mobile phone data. *Int. J. Epidemiol.* **47**(5), 1562–1570 (2018). <https://doi.org/10.1093/ije/dyy095>
- Roudbari, A., Nateghi, A., Yousefi-khanghah, B., Asgharpour-Alamdari, H., Zare, H.: Resilience-oriented operation of smart grids by rescheduling of energy resources and electric vehicles management during extreme weather condition. *Sustain. Energy Grids Netw.* **28**, 100547 (2021). <https://doi.org/10.1016/j.segan.2021.100547>
- Roy, K.C., Cebrian, M., Hasan, S.: Quantifying human mobility resilience to extreme events using geo-located social media data. *EPJ Data Sci.* **8**(1) (2019). <https://doi.org/10.1140/epjds/s13688-019-0196-6>
- Tamvakis, P., Xenidis, Y.: Resilience in transportation systems. *Procedia Soc. Behav. Sci.* **48**, 3441–3450 (2012). <https://doi.org/10.1016/j.sbspro.2012.06.1308>
- Teixeira, J.F., Silva, C., Moura e Sá, F.: The motivations for using bike sharing during the COVID-19 pandemic: insights from Lisbon. *Transp. Res. Part F Traffic Psychol. Behav.* **82**, 378–399 (2021). <https://doi.org/10.1016/j.trf.2021.09.016>
- Twumasi-Boakye, R., Sobanjo, J.O.: Resilience of regional transportation networks subjected to hazard-induced bridge damages. In *J. Transp. Eng. Part A Syst.* **144**(10), Article 04018062 (2018). <https://doi.org/10.1061/JTEPBS.0000186>
- van der Horst, R.S.N., Ettema, D.: Use of travel information and effects on mode choice for recreational trips. In: *Transportation Research Board 84th Annual Meeting* (2005)
- van Exel, N.J.A., Rietveld, P.: When strike comes to town...anticipated and actual behavioural reactions to a one-day, pre-announced, complete rail strike in the Netherlands. *Transp. Res. Part A Policy Pract.* **43**(5), 526–535 (2009). <https://doi.org/10.1016/j.tra.2009.01.003>

- Wan, C., Yang, Z., Zhang, Di., Yan, X., Fan, S.: Resilience in transportation systems: a systematic review and future directions. *Transp. Rev.* **38**(4), 479–498 (2018). <https://doi.org/10.1080/01441647.2017.1383532>
- Wang, Q., Taylor, J.E.: Resilience of human mobility under the influence of typhoons. *Procedia Eng.* **118**, 942–949 (2015). <https://doi.org/10.1016/j.proeng.2015.08.535>
- Wang, Q., Taylor, J.E.: Patterns and limitations of urban human mobility resilience under the influence of multiple types of natural disaster. *PLoS ONE* **11**(1), e0147299 (2016). <https://doi.org/10.1371/journal.pone.0147299>
- Wu, H.-C., Lindell, M.K., Prater, C.S.: Logistics of hurricane evacuation in Hurricanes Katrina and Rita. *Transp. Res. Part F Traffic Psychol. Behav.* **15**(4), 445–461 (2012). <https://doi.org/10.1016/j.trf.2012.03.005>
- Yin, W., Murray-Tuite, P., Ukkusuri, S.V., Gladwin, H.: An agent-based modeling system for travel demand simulation for hurricane evacuation. *Transp. Res. Part C Emerg. Technol.* **42**, 44–59 (2014). <https://doi.org/10.1016/j.trc.2014.02.015>
- Zhou, Y., Wang, J., Yang, H.: Resilience of transportation systems: concepts and comprehensive review. *IEEE Trans. Intell. Transp. Syst.* **20**(12), 4262–4276 (2019). <https://doi.org/10.1109/TITS.2018.2883766>
- Zhu, S., Levinson, D.M.: A review of research on planned and unplanned disruptions to transportation networks. In: *Transportation Research Board 89th Annual Meeting* (2010)

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

