Resilience of Transport Systems

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Abstract: The transport system is an infrastructure that is critical to society. This is clearly demonstrated when the system is exposed to a shock. We discuss the significance of transport resilience and the related concepts of risk and vulnerability. Shocks to the transport system can be internal or external, natural or human-made, intentional or unintentional. Different transport systems are more or less susceptible depending on their robustness, redundancy and measures introduced to improve resilience. Future electrified autonomous vehicles can reduce resilience. Moreover, climate change can increase the frequency of extreme weather disturbances. Many tools have been developed to study the vulnerability of transport systems and to evaluate proposed measures to enhance resilience. Hopefully, their continued implementation and new research findings will further strengthen the resilience. The experience from Covid-19 shows that human adaptability and ingenuity when exposed to crises are very large – an unplanned and unexpected form of resilience.

Keywords: betweenness, Covid-19, critical, disaster, disruption, infrastructure, mobility, networks, resilience, risk, robustness, shock, transport, travel, vulnerability.

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Resilience of Transport Systems

Introduction
Our daily lives as well as society at large have become increasingly dependent on critical infrastructure systems providing amenities such as electric power supply, information and telecommunications (ICT) and, not least, mobility and freight transport. Over time, the systems have become more complex and intertwined, with consequences of disruptions that are difficult to identify, understand and mitigate. Because they are critical to society, their resilience, i.e., ability to resist, absorb, adapt and quickly recover from shocks, disruptions and deliberate attacks, has become an important societal goal.

The transport system can conceptually be divided into three parts (Figure 1):
1) technical and physical infrastructure including rails, roads, terminals, airports, ports, vehicles, signals, signs, etc.,
2) direct and indirect users of the technology, i.e., travelers, transporters and society in general,
3) actors responsible for planning, operating and maintaining the infrastructure and services under given regulations and budget restrictions.

Figure 1. A trisecting model of the transport system.

Shocks to the transport system can initiate in any of the three parts and then propagate to the other parts. Infrastructure disruptions are caused by, e.g., technical failures (bridge collapses, power outages, vehicle malfunctions, etc.), extreme operating conditions (floods, snow storms, etc.) or deliberate attacks. User disruptions can occur due to economic crises, conflicts and health crises such as the Covid-19 pandemic. Disruptions in the management may arise from, for example, political shifts or labor conflicts. Climate change will be an increasing threat primarily to the transport infrastructure. Ironically, the transport system has contributed to this threat through its hitherto almost total dependence on fossil fuels.

Societal shocks can be completely unexpected. While the risk of a pandemic was known, Covid-19 had cascading effects on the economy and the transport system to an extent never seen before. The surprisingly rapid global spread of Covid-19 is, in part, explained by the extreme level of mobility offered by today’s transport system (Musselwhite et al., 2020; Peeri et al., 2020). Most countries sought to suppress the spread by closing borders and restricting mobility locally and globally as well as locking down activities and businesses. This led to a drastic reduction in travel demand, followed by a corresponding reduction in supply. The effects were most pronounced for the aviation industry. Public transport, including rail, was also greatly affected. However, the transport infrastructure was left intact.
Resilience and related concepts

Holling (1973) introduced resilience as a term for an ecological system’s ability to absorb changes and shocks and still persist. Another ecologist, Pimm (1984), defined resilience as the rapidity with which a system returns to equilibrium after a perturbation. Both these views are typically included in recent definitions of the resilience of transport systems. Rose (2007), for instance, expresses this as a distinction between static resilience, a system’s capability to maintain its function, and dynamic resilience, the rate at which a system returns to equilibrium after a disturbance. Bruneau et al. (2003) understand a resilient system as one that has reduced the probabilities of shocks, that exposed to a shock experiences moderate consequences, and that recovers quickly. A large number of similar definitions have been suggested. We summarize them as follows (inspired in particular by UNISDR, 2009):

**Definition**

*Resilience* is the ability of a transport system to prepare for and to withstand, absorb and adapt to shocks, and to recover from the consequences in a timely and efficient manner.

Bruneau et al. (2003) specify four properties that characterize a resilient system: robustness, redundancy, resourcefulness, and rapidity. Robustness reflects the ability to withstand shocks without or with only limited degradation of service. Redundancy reflects the extent to which there are alternative units that can function as substitutes and hence absorb the consequences of degradation. Resourcefulness reflects the capacity to identify problems, prioritize actions and mobilize necessary material and human resources to adapt and recover the system. Rapidity reflects the capacity to recover in a timely and efficient manner. The robustness and redundancy represents the static aspect of resilience, whereas resourcefulness and rapidity represents the dynamic aspect.

The relation between different concepts is illustrated in Figure 2. The area between the straight horizontal line and the curved line below represents the total loss of function, i.e., lack of resilience against a specific shock (Bruneau et al., 2003).\(^1\) This lack is obviously dependent on ex ante mitigation

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\(^{1}\) The lack of resilience \( R \) can be represented quantitatively as

\[
R = \int_{t_0}^{t_1} \left[ Q_0 - Q(t) \right] dt,
\]

where \( Q_0 \) is the normal and \( Q(t) \) the time-varying quality of service (system function) between the time \( t_0 \), when the shock occurs, and the time \( t_1 \), when the function is restored to its pre-shock level.
measures and ex post adaptation measures that have been taken. The figure does not represent the extent to which the likelihood of shocks has been reduced but presents the situation conditional on that a shock has occurred. This may be termed conditional resilience.

There are many related concepts, in particular risk and vulnerability. Following Kaplan and Garrick (1981), risk can be defined as a set of triplets, each one consisting of a scenario, the probability and the consequence in terms of damage resulting from the scenario. The scenario is a description of a chain of (unwanted, negative) events that can happen. The consequence corresponds to conditional lack of resilience. Measures taken by the system owner to strengthen the system become part of risk management.

Vulnerability of a transport system may be defined as a susceptibility to events that can result in considerable reductions in transport system serviceability (Berdica, 2002) or, with a shorter but similar formulation, as society’s risk of transport system disruptions and degradation (Jenelius and Mattsson, 2015). Vulnerability studies aim at finding the weaknesses in a system, estimating the probabilities that they will lead to serious deterioration and the consequences thereof. The term vulnerability is often used even if there is no attempt to determine the probability of disruption. When a distinction is necessary, this may be termed conditional vulnerability. A vulnerability study can help the system manager identify the critical elements of a system and which preventive measures that would be most valuable. Vulnerability as opposed to resilience studies are thus more limited and are primarily focused on how the robustness of a system can be strengthened. In Figure 2, conditional vulnerability corresponds to how deep the system function will decrease when subject to a shock, or the normal level of function minus the robustness.

Causes and consequences of disruptions
Disruptions in transport systems can take many forms (see Table 1). It is useful to distinguish between disruptions caused by “nature”, technical failures and unintentional errors on the one hand, and disruptions caused by malign individuals on the other hand. In the first case, there is a certain

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2 Formally they define $\text{risk} = \{\{\text{scenario}, \text{probability}, \text{consequence}\}\} \quad i = 1, 2, ..., I$.  

3 Formally, conditional vulnerability is $Q_0 - \min_{t \in [t_0, t_1]} Q(t)$.  

Table 1. Causes of disruptions in transport infrastructure.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Natural</th>
<th>Human-made unintentional</th>
<th>Human-made intentional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside</td>
<td>Technical failure</td>
<td>Accident, handling error, negligence</td>
<td>Malicious insider, labor market dispute</td>
</tr>
<tr>
<td>Outside</td>
<td>Natural disaster, earthquake, extreme weather, technical failure</td>
<td>Accident, handling error, negligence</td>
<td>Act of war, terrorist attack, criminal action, prank</td>
</tr>
</tbody>
</table>

element of randomness as to when and where disruptions occur. Internal threats in the form of technical failures, accidents and handling errors fall within the domain of system managers with more direct control compared to external causes. In some cases, a combination of both technical and human factors contributes to initiate and exacerbate the incident.

The transport system is also heavily exposed to external threats such as disasters, extreme weather and technical failures in other infrastructure. The unexpectedness of many of these threats makes it difficult to protect the transport system. Table 2 lists a few examples of weather-related transport system disruptions. As climate change continues, extreme weather can be expected to become more common and its effects on transport more severe (Koetsee and Rietveld, 2009).

External threats also include deliberate attacks such as sabotage, terrorism and acts of war. Tragically, almost all modes of transport have been subject to deadly terrorist attacks. An intelligent adversary can be expected to look for vulnerabilities in a system and where and when it is poorly protected. A malicious insider can be particularly well informed about a system's vulnerabilities. Since the transport system is critical for companies and people, it is also often exposed to labor market conflicts, not least in labor-intensive modes such as air, rail and public transport. Table 3 lists some notable historical disruptive events.

Different transport subsystems, or modes, have different resilience characteristics. The road transport system provides the majority of all inland passenger and tonne kilometers transported. Road transport is characterized by relatively high levels of independence for the users and redundancy in routes. This implies that the users are well equipped to handle disruptions through detours and rescheduling. Remote areas may be vulnerable to disruptions at a particular critical location, for example a bridge, while urban areas can suffer from cascading congestion and queues. Even in dense networks, area-covering disruptions such as floods can have severe consequences (Jenelius and Mattsson, 2015).

Compared to roads, rail traffic is characterized by substantially more regulation and control. The system is dependent on other critical infrastructure, in particular the electric power grid. The dependence on labor, ICT systems as well as mechanical and electric systems is also high. Route redundancy is typically low, and overtaking stopped trains is difficult if not impossible. These factors contribute to make the rail system relatively sensitive to disruptions.

Air traffic is characterized by high safety and security concerns coupled with private market competition and strong dependencies on labor, fuel supply, ICT and electric systems. The network consists of nodes (airports) with strict regulations and interdependencies between vehicles and journeys, and links (flights) with high degrees of freedom concerning flight path and speed. Disturbances that tend to originate at nodes can lead to knock-on delays and missed connections.
Table 2. Examples of weather-related transport system disruptions (adapted from Leviäkangas et al., 2011).

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Transport mode</th>
<th>Possible infrastructure impacts</th>
<th>Possible effects on users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy snowfall</td>
<td>Road</td>
<td>Drainage blocking, road and bridge destruction, road blocking</td>
<td>Slow driving speed, reduced accessibility, cancelled trips</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>Track damage and blocking, electricity loss, freezing of switches</td>
<td>Stopped and cancelled trains, lower speeds, accidents</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>Blocked runways</td>
<td>Delays, cancelled flights</td>
</tr>
<tr>
<td>Heavy rain</td>
<td>Road</td>
<td>Drainage blocking, road and bridge destruction, road flooding</td>
<td>Slow driving speed, reduced accessibility, cancelled trips</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>Track damage and blocking</td>
<td>Stopped and cancelled trains, lower speeds, accidents</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>Blocked routes, closed airports</td>
<td>Delays, cancelled and diverted flights</td>
</tr>
<tr>
<td>Drought</td>
<td>Road</td>
<td>Forest fires, road damage and blocking</td>
<td>Reduced accessibility, cancelled trips</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>Forest fires, track damage and blocking, electricity loss</td>
<td>Stopped and cancelled trains</td>
</tr>
<tr>
<td>Waterway (inland)</td>
<td>Waterway</td>
<td>Lower water levels</td>
<td>Slow speed, reduced carrying capacity, reduced accessibility</td>
</tr>
<tr>
<td>Heavy wind</td>
<td>Waterway</td>
<td>Ship and port damage, stopped or cancelled ferries</td>
<td>Delays, accidents</td>
</tr>
<tr>
<td>Air</td>
<td>Reduced ground, take-off and landing speed, turbulence</td>
<td>Delays, accidents, discomfort</td>
<td></td>
</tr>
<tr>
<td>Sandstorm, volcanic ash</td>
<td>Air</td>
<td>Airspace closed, engine damage</td>
<td>Delays, cancelled and diverted flights</td>
</tr>
</tbody>
</table>

Table 3. Examples of transport system disruptions.

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Location, date</th>
<th>Initiating event</th>
<th>Transport system damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterway (maritime)</td>
<td>Baltic Sea, 1994</td>
<td>Rough weather, damaged bow visor</td>
<td>Passenger ferry sank, 852 died from drowning and hypothermia</td>
</tr>
<tr>
<td>Rail</td>
<td>Madrid, 2004</td>
<td>Terrorist bomb</td>
<td>Train cars exploded, 193 died, some 2000 injured</td>
</tr>
<tr>
<td>Air</td>
<td>Iceland, 2010</td>
<td>Volcanic ash cloud</td>
<td>European airspace closed for more than a week</td>
</tr>
<tr>
<td>All</td>
<td>Chile, 2010</td>
<td>Earthquake followed by tsunami</td>
<td>All transport infrastructure seriously damaged, officially 525 died, 25 missing</td>
</tr>
<tr>
<td>Public transport and other modes</td>
<td>New York, 2012</td>
<td>Hurricane Sandy</td>
<td>Flooding, subway and other traffic stopped for 5 days or more</td>
</tr>
<tr>
<td>Road</td>
<td>Genoa, 2018</td>
<td>Rain, technical failure under investigation</td>
<td>Collapsed bridge, 43 died and 16 injured</td>
</tr>
</tbody>
</table>

https://en.wikipedia.org/wiki/MS_Estonia,
https://en.wikipedia.org/wiki/Air_travel_disruption_after_the_2010_Eyjafjallaj%C3%B6kull_eruption
https://en.wikipedia.org/wiki/2010_Chile_earthquake,

Public transport can offer efficient mobility in urban areas as well as base levels of accessibility in remote areas, and can be provided in the road, rail, waterway and even air transport systems. Depending on the transport mode, public transport is thus subject to the vulnerabilities of each system discussed above. The system is further characterized by the schedule-based operations, and traffic disturbances may lead to long in-vehicle travel times, waiting times, crowding and denied boarding.

Consequences of disruptions range from annoying delays, missed travel connections, interrupted trips and delayed goods deliveries, to a decline in the economy due to reduced transportation opportunities and, not least, injuries and deaths due to accidents, disasters or deliberate attacks. It is challenging to evaluate these very different dimensions in a one-dimensional consequence indicator. Cost-benefit analysis of transport policy measures may possibly serve as an example. The effects on accidents, the environment, accessibility and wider economic benefits are then summarized in a monetary value according to a well-defined procedure. However, shocks have impacts in dimensions not typically included in traditional cost-benefit analysis. Taking Covid-19 as an example, although the consequences for the transport system were very significant, the major consequences were in terms of people’s life, health, and the effects on the economy. Exceptional events may also affect citizens’ perceived security and their confidence in the public institutions’ ability to protect them. Such effects are difficult to value in monetary terms. Since different social strata and different geographical areas are affected unevenly by a disruption, fairness aspects must also be taken into account.

Tools to study resilience
Data on past disruptions can provide valuable information to better prepare for future threats. This is especially relevant for natural and unintentional human-made disruptions. For intentional attacks, historical data has less relevance for where and when future attacks may occur, as an adversary likely wants to surprise a defender.
It is intuitive to conceptualize transport infrastructure as a network or graph, comprising a set of nodes (or vertices) and a set of links (or edges) in which each link connects two nodes. The appropriate network representation of the system depends on the scope of the analysis. A common representation of the air transport system, for example, is to model airports as nodes and connections or specific flights as links. The basic node and link structure is known as the topology of the network. On top of the topology can be added other properties such as link weights (e.g., lengths or costs) and capacity constraints. The most sophisticated network models involve detailed dynamic, sometimes stochastic, simulation of the interactions between vehicles and the stationary infrastructure (Bell and Iida, 1997; de Dios Ortúzar and Willumsen, 2011).

A network model can be used to analyze the resilience against disruptions represented as failures/removals of nodes or links. A simple measure of network connectivity is the relative size of the largest connected component of the network, i.e., the largest number of nodes that can be reached from each other through at least one network route. Another measure is the average distance between all node pairs, where distance is defined as the length of the shortest path connecting each node pair. If the network is not connected, which may happen after link and node removals, the average distance becomes infinite. Latora and Marchiori (2001) introduce an efficiency indicator defined as the average across all node pairs of the reciprocals of the node pair distances. This indicator is well defined also for non-connected networks, and the change in efficiency can be used as a vulnerability metric.

There is an important connection between the resilience and vulnerability of a transport network and its topological structure, in particular the existence and location of central nodes and links (Reggiani, 2013; Zhang et al., 2015). A simple local measure of node centrality is the degree, i.e., the number of links connecting directly to the node. In the air transport network example, the degree of a node is the number of routes or flights connecting an airport to other airports. High-degree nodes are sometimes known as hubs. The distribution of degrees among network nodes has attracted considerable interest. The network is said to be scale-free if the degree distribution follows a power law, at least asymptotically, i.e., decreases as \( k^{-\gamma} \) for large values of the degree \( k \). The exponent \( \gamma \) is typically between 2 and 3. Scale-free networks are considered robust to random failures but vulnerable to successful attacks on high-degree nodes (Lin and Ban, 2013). A global measure of node centrality is betweenness, which is the number of shortest paths between all other node pairs that include the node. In the air transport network, high betweenness indicates that the airport is an important transfer location. Degree and betweenness are illustrated in Figure 3.

The network-modeling paradigm can be extended to include the transport users, in particular travelers and goods. These can be modeled as travel demand between special source (origin) and sink (destination) nodes, which enters the network as link flows. More elaborate network models

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4 In mathematical terms, the efficiency metric is defined as \( E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}}, \) where \( V \) is the node set, \( N \) is the number of nodes, and \( d_{ij} \) is the network distance between nodes \( i \) and \( j \).

5 Formally, the (conditional) vulnerability to a removal of node \( i \) can be defined as \( E_0 - E_i \), where \( E_0 \) is the efficiency of the nominal network and \( E_i \) is the efficiency with node \( i \) removed.
may incorporate congestion (flow-dependent link costs), demand routing mechanisms, dynamic and stochastic demand, etc. Including transport demand in the network model allows for more nuanced metrics of resilience against node and link removals. A useful measure is the *unsatisfied demand*, defined as the amount of flow, which is unable to reach its destinations. If each link is associated with a travel time (or cost), a meaningful resilience metric is the increase in total travel time (or cost) (Jenelius and Mattsson, 2015). Figure 4 illustrates the potential impacts of link removals.

At the finest level of detail, agent-based models can represent each traveler and vehicle as an individual object with unique properties. Such frameworks can be used to capture the dynamic dimension of resilience, including the deterioration and eventual restoration of system function associated with a disruption (Malandri et al., 2018).

Different types of disruptive events require different modeling approaches. Disruptions caused by "nature" or unintentional human actions are often appropriately modeled as removals of randomly selected nodes or links. Random removals of multiple links or nodes can be studied as well but increases the combinatorial complexity.

Disruptions caused by intentional human interventions are likely targeted towards network components where they can achieve as much damage as possible. Data on past attacks will then say little about future attacks. It may be better to analyze who may be interested in and capable of...
performing such an attack. A commonly studied strategy is to attack the nodes with the highest degree, thereby disrupting as many local connections as possible. Another strategy is to target the global connectivity by attacking the nodes with the highest betweenness centrality or transport flow. Some studies evaluate resilience in terms of how network function deteriorates as increasing numbers of nodes are removed (e.g., Zhang et al., 2016).

A characteristic feature of intentional attacks is that the strategy for targeting network components can adapt to measures taken by society to protect the system. Thus, protecting the most vulnerable components from attacks could divert attacks to other, less protected components. Here, game theory can provide insights into the risk for attacks across the transport. For example, consider a situation when an antagonist wants to disrupt freight transport by attacking a network link, while the transporter wants to route the freight to minimize the expected losses. In this case, optimal strategies for the transporter can be found by studying the Nash equilibria of the conflict, i.e., strategy combinations under which no actor can single-handedly increase its payoff by changing strategy (Bell et al., 2008).

**Enhancing resilience**

Since resilience is a multifaceted concept, a set of proactive and reactive measures is required to enhance it. To some extent, potential threats may be avoided. For actions such as investments in new railways, roads and other physical infrastructure, national transport authorities have the capacity to make the decisions. To some extent, they can avoid sites that are exposed to natural threats like floods, landslides and adverse weather. However, trying to protect the transport system from any conceivable threat or disruption would be prohibitively expensive. The most challenging example is climate change. If effective measures to stop or at least limit climate change are implemented, the expected increase in extreme weather can be reduced. To realize such a policy, decisions outside the transport system at an international political level are necessary.

For shocks like earthquakes, tsunamis and deliberate attacks, it is impossible to predict with accuracy where and when they will occur. Other shocks are hardly possible to imagine in advance. This was the case with the transport impacts of Covid-19 through the measures taken to limit its spread. Therefore, reactive measures to withstand, absorb and adapt to shocks are also necessary. The properties that characterize a resilient system, robustness, redundancy, resourcefulness, and rapidity, are helpful in structuring such considerations (Bruneau et al., 2006).
Robustness and redundancy are primarily associated with the static aspect of resilience. A robust transport system can withstand shocks with no or limited degradation of service. Roads, bridges, railways, drainage and other critical technical elements can be built to withstand and absorb considerable external stress and planned to be regularly inspected, repaired and maintained. The most obvious example of increasing the resilience of a transport network through redundancy is to add links to increase the number of alternative routes. Different transport modes can partly substitute for each other. Reserve capacity for personnel and vehicles in, for example, public transport, can help coping with increased sick leave or sudden technical problems. The tools discussed in the previous section are valuable for identifying the elements in the transport networks that are most critical to strengthen and maintain, and the degree to which increased redundancy can absorb the consequences of degradations. Table 4 provides examples of policy instruments to enhance resilience against flooding in an Indian context.

Resourcefulness and rapidity are primarily associated with the dynamic aspect of resilience, i.e., reducing the total consequences through timely mitigation and restoration. Resourcefulness reflects the ability to identify problems, prioritize actions and mobilize necessary material and human resources to adapt and recover the system. The capacity to handle disruptions can be strengthened through a high level of readiness, including relevant equipment and personnel who are well trained in handling the equipment and dealing with accidents and disasters. Adequate information systems to alarm rescue forces about disruptions and help them coordinate relief efforts are important. In addition, resources must be available to reduce the consequences for those directly or indirectly affected by a disruption. Travelers often have to wait for hours at airports, on stopped trains or in car queues. Such consequences can be partially mitigated by providing travelers with relevant information to facilitate their own decisions. In order to ensure that the transport system is well prepared to minimize the consequences of disruptions, a number of measures must be implemented. Table 5 gives some examples from the UK of recommended preventive measures to improve the transport system's resilience to extreme weather.

**Ongoing trends**
Continued technological development can be expected to make infrastructure systems increasingly intertwined. Among the transport subsystems, the road system has been the least dependent on other infrastructure systems. The development of connected autonomous vehicles may change this through the need to communicate wirelessly with other vehicles, infrastructure and global satellite navigation systems. Moreover, if a vehicle loses contact with the support systems, it must be able to stop safely. Mobility-as-a-service is new concept that requires reliable wireless communication for

<table>
<thead>
<tr>
<th>Phase</th>
<th>Mechanism</th>
<th>Action</th>
<th>Effect on transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proactive</td>
<td>Avoidance</td>
<td>Restricting development in low lying or vulnerable areas</td>
<td>Fewer travelers exposed to flooding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slum relocation and rehabilitation</td>
<td>Fewer travelers exposed to flooding</td>
</tr>
<tr>
<td>Robustness</td>
<td></td>
<td>Providing proper drainage facilities at vulnerable areas</td>
<td>Decreased road inundation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Replacement of impermeable road surface with permeable material in vulnerable areas</td>
<td>Decreased road inundation</td>
</tr>
<tr>
<td>Redundancy</td>
<td></td>
<td>Construction of redundant infrastructure</td>
<td>More route options</td>
</tr>
<tr>
<td>Reactive</td>
<td>Adaptation</td>
<td>Rerouting people during flooding</td>
<td>Travelers less affected by flooding</td>
</tr>
</tbody>
</table>
Table 5. Examples of recommended preventive actions to enhance resilience to extreme weather events (adapted from Department of Transport, 2014).

<table>
<thead>
<tr>
<th>Preventive actions to enhance resilience to extreme weather events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consider whether there are potential 'single points of failure' in the networks, which leave parts of the country at risk of having vital economic and social links severed.</td>
</tr>
<tr>
<td>Identify a 'critical network', comprising those routes which are of national economic significance and should be maintained to a higher level.</td>
</tr>
<tr>
<td>All transport operators should have contingency plans to cope with extreme weather events.</td>
</tr>
<tr>
<td>Contingency plans should be regularly rehearsed and progressively extended.</td>
</tr>
<tr>
<td>All transport operators should ensure they have clearly agreed channels for receiving weather and flood forecasts.</td>
</tr>
<tr>
<td>All transport operators and authorities should implement a dedicated passenger and user communications plan for times of transport disruption.</td>
</tr>
<tr>
<td>In the face of an extreme weather event, transport operators should plan for the best practicable service which they can realistically deliver.</td>
</tr>
<tr>
<td>Transport operators should have checklists of resources which they will need as part of their recovery effort.</td>
</tr>
<tr>
<td>Rail infrastructure operator should liaise with its electricity suppliers to trace through the routes and sub-stations to ensure adequate system redundancy.</td>
</tr>
<tr>
<td>Contingency rail timetables should be prepared to match different weather events.</td>
</tr>
<tr>
<td>Rail infrastructure operator should have adequate resources available for clearing fallen trees.</td>
</tr>
</tbody>
</table>

ordering and operating the vehicles. Since the communication is vulnerable to intentional and unintentional disturbances, it is necessary to make the communication reliable and secure. Another important trend affecting particularly the road transport system is the electrification of vehicles, which increases the dependence on the electric power system. A resilient road transport system with self-driving electrified vehicles requires both interference-free wireless communication and reliable electricity supply.

Climate change has far-reaching consequences for transport. Extreme weather such as hurricanes, heavy rain and drought are forecasted to become more common. This will lead to a higher frequency

of disruptions in the transport networks due to, e.g., storm-felled trees, landslides, floods and forest fires. Further, policies aimed at reducing carbon emissions and reaching the Agenda 2030 sustainable development goals will by necessity create significant shocks to transport users through changes in vehicle technologies, regulations, taxes, fuel prices, ticket and shipping prices, etc.

The impact of the Covid-19 pandemic on mobility and demand for transport has been profound. To stop the spread of the virus, authorities locked down many activities and drastically restricted physical contacts and mobility. The responses to these actions illustrate the flexibility and adaptability that exists in society. The biggest adjustment made by individuals in both private and working life is arguably the change from physical to virtual contacts. Since this requires access and familiarity with, e.g., video conferencing systems, it is reasonable to assume that many will continue to meet virtually also after Covid-19 once this effort has been made. Whether it will reduce travel in the long run remains to be seen. Covid-19’s stimulus of e-commerce is another effect that can be lasting. In the aviation sector, demand fell almost to zero and many companies have gone bankrupt or needed great financial support from governments to survive. When air traffic resumes to a fairly normal level, ticket prices and freight rates are likely to be higher than before the pandemic. Combined with the debate on the climate effects of aviation, this may lead to a significant, lasting reduction in air traffic. The increased familiarity with video conferences may further contribute to this. The impacts on transport resilience of these potential mobility effects are difficult to speculate about. However, what we have learned from Covid-19 is that human adaptability and ingenuity are very large when sudden changes occur. This is an unplanned and unexpected form of resilience.

Concluding remarks

By resilience is meant a transport system’s ability to prepare for and to withstand, absorb and adapt to shocks, and to recover from the consequences in a timely and efficient manner. The significance of transport systems makes their resilience an important policy issue. Transport also has a key role for other infrastructure systems in facilitating rescue and repair personnel to get quickly in place to handle the consequences after a disruption. The severity of shocks to the transport systems can vary widely, as well as the causes. Different transport systems exhibit different characteristics from a resilience perspective, depending, for example, on how the behavior of the users is regulated. In the road system, users can often make detours to avoid disrupted links. The rail system is substantially more regulated and rerouting is decided at the level of traffic control.

Research on resilience, risk and vulnerability of transport systems has exploded the last two decades. Tools to study resilience have been developed that can help identifying vulnerabilities in the systems. The tools are also helpful in evaluating measures to enhance resilience. Hopefully, the implementation of new research findings will help decision-makers to make the transport systems less vulnerable and more resilient.

References


Berdica, K., 2002. An introduction to road vulnerability: What has been done, is done and should be done. Transport Policy 9, 117–127.


**Further reading**


**Websites**

www.instr.org
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www.trb.org
TRB, Transportation Research Board
www.gov.uk/government/organisations/department-for-transport
UK Department for Transport
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UNDRR, United Nations Office for Disaster Risk Reduction
www.transportation.gov
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**Cross references**

10013, 10219, 10300, 10301, 10302, 10318, 10358