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Large-Scale Road Network Vulnerability Analysis

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Abstract

Disruptions in the transport system can have severe impacts for affected individuals, businesses and the society as a whole. In this research, vulnerability is seen as the risk of unplanned system disruptions, with a focus on large, rare events. Vulnerability analysis aims to provide decision support regarding preventive and restorative actions, ideally as an integrated part of the planning process.

The thesis specifically develops the methodology for vulnerability analysis of road networks and considers the effects of suddenly increased travel times and cancelled trips following road link closures. The major part consists of model-based studies of different aspects of vulnerability, in particular the dichotomy of system efficiency and user equity, applied to the Swedish road network. We introduce the concepts of link importance as the overall impact of closing a particular link, and regional exposure as the impact for individuals in a particular region of, e.g., a worst-case or an average-case scenario (Paper I). By construction, a link is important if the normal flow across it is high and/or the alternatives to this link are considerably worse, while a traveller is exposed if a link closure along her normal route is likely and/or the best alternative is considerably worse. Using regression analysis we show that these relationships can be generalized to municipalities and counties, so that geographical variations in vulnerability can be explained by variations in network density and travel patterns (Paper II). The relationship between overall impacts and user disparities are also analyzed for single link closures and is found to be negative, i.e., the most important links also have the most equal distribution of impacts among individuals (Paper III).

In addition to links' roles for transport efficiency, the thesis considers their importance as rerouting alternatives when other links are disrupted (Paper IV). Such redundancy-important roads, found often to be running in parallel to highways with heavy traffic, may be warranted a higher standard than their typical use would suggest. We also study the vulnerability of the road network under area-covering disruptions, representing for example flooding, heavy snowfall or forest fires (Paper V). In contrast to single link failures, the impacts of this kind of events are largely determined by the population concentration, more precisely the travel demand within, in and out of the disrupted area itself, while the density of the road network is of small influence. Finally, the thesis approaches the issue of how to value the delays that are incurred by network disruptions and, using an activity-based modelling approach, we illustrate that these delay costs may be considerably higher than the ordinary value of time, in particular during the first few days after the event when travel conditions are uncertain (Paper VI).

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List of Papers

- I Jenelius, E., Petersen, T. and Mattsson, L.-G. (2006) Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice* 40(7), 537–560.
- II Jenelius, E. (2009) Network structure and travel patterns: Explaining the geographical disparities of road network vulnerability. *Journal of Transport Geography* 17(3), 234–244.
- III Jenelius, E. (2010a) User inequity implications of road network vulnerability. *Journal of Transport and Land Use* 2(3/4), 57–73.
- IV Jenelius, E. (2010b) Redundancy importance: Links as rerouting alternatives during road network disruptions. *Procedia Engineering* 3, International Conference on Evacuation Modelling and Management, 129–137.
- V Jenelius, E. and Mattsson, L.-G. (2010) Road network vulnerability analysis of area-covering disruptions: A grid-based approach with case study. Submitted.
- VI Jenelius, E., Mattsson, L.-G. and Levinson, D. (2010) The traveler costs of unplanned transport network disruptions: An activity-based modeling approach. Submitted.

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Large-Scale Road Network Vulnerability Analysis

Our world is dominated by the extreme, the unknown, and the very improbable (improbable according to our current knowledge)—and all the while we spend our time engaged in small talk, focusing on the known, and the repeated.

Nassim Nicholas Taleb, *The Black Swan*, 2007

1. Introduction

Modern society relies upon the collection of systems and institutions known as the infrastructure to provide comfort and security for the people. Some of these systems are more fundamental than others in the sense that they supply services that other systems require. These most basic systems include housing, water supply, heating, communications and—the focus of the present thesis—various modes of transport. On these more elaborate institutions and services are built, such as health care, law enforcement, waste management, education and finance. There also exist interdependencies between systems, for example electric power and data communications, so that the performance of one system depends on the other and vice versa (e.g., Rinaldi et al., 2001; Little, 2002).

The welfare and living standard of a society is intrinsically linked to the level at which its infrastructure is developed and maintained. A downside of this dependency, perhaps almost equally intrinsic, is that sudden failures and disruptions in the systems can cause severe strains on the society. The systems of which degradations would have the largest negative impacts are often collectively referred to as the *critical infrastructure*. The constituting systems may vary between countries and the evaluation criteria used, but have invariably included transport systems in general and the road transport system in particular (for USA, see, e.g., Moteff and Parfomak (2004); for Sweden, see KBM (2005)).

We use the term vulnerability analysis to refer to the study of potential degradations of the infrastructure and their impacts on society. Infrastructure vulnerability

is thus the extent to which infrastructure disruptions lead to reductions in the welfare of the society, or simply put, the *risk* of infrastructure disruptions; see further Section 2. This thesis focuses on the road transport system, more specifically on disruptions of components in the road network (roads and intersections). *Road network vulnerability analysis* is thus a special case of infrastructure vulnerability analysis, which suggests that many concepts and approaches found in the broader field are relevant here, and vice versa. At the same time, each infrastructure system has its own inherent purposes and characteristics that need to be taken into account in a vulnerability analysis. This thesis contributes concepts and perspectives that are generally applicable and useful in infrastructure vulnerability analysis, as well as metrics, models and analyses that are specific to the road transport system.

2. Vulnerability, risk and reliability

The word vulnerability is used in every-day language to express a sensitivity to attack or injury. As is often the case with popular terms, there is no generally adopted notion of what road transport or infrastructure vulnerability is. For example, Willis (2007) focuses on the ability to withstand an attack and defines vulnerability as the probability that an attack results in damage, given that an attack occurs. Taylor et al. (2006) defines a node in a road network to be vulnerable “if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, as measured by a standard index of accessibility”. Thus, whereas some authors stress the probability of negative consequences, others stress the magnitude of the negative consequences. Still other views are proposed by, e.g., Einarsson and Rausand (1998), Haines (2006), Aven (2007), Ezell (2007) and Johansson (2010). We shall not attempt a full literature review of the vulnerability concept here; a further discussion is found in Paper I.

In this thesis we propose that *vulnerability is risk*, where our notion of risk is adopted from Kaplan and Garrick (1981), with a focus on a particular kind of scenarios. According to those authors, a risk analysis consists of answering three questions: (i) What can happen? (ii) How likely is it that that will happen? and (iii) If it does happen, what are the consequences? The results of the analysis can thus be represented as a list of “triplets”, each consisting of a description of a particular scenario, the probability of that scenario occurring, and the impact of the scenario. The risk is then the set of all triplets. If the impact of each scenario is expressed as a single number, sorting the scenarios according to increasing impacts and plotting the probability that the impact is larger than a given value gives a representation of the risk known as the “risk curve”; see Figure 1 for an illustration.

In our view, then, infrastructure vulnerability is society’s risk of infrastructure system disruptions and degradations. Based on the general definition of risk from Kaplan and Garrick (1981), we have thus defined the target for which the impacts

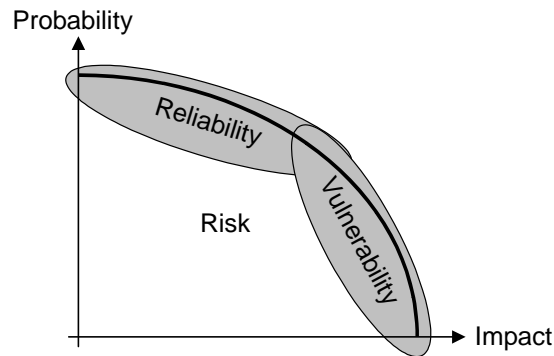


Figure 1: Illustration of the relationships between road transport system disruption risk, vulnerability and reliability as perceived in this thesis. The thick line represents the “risk curve” of Kaplan and Garrick (1981), i.e., the probability that the impact is greater or equal to a given value.

are to be assessed (although very generally), i.e., the society. We have also put restrictions on the kind of scenarios that we consider, i.e., infrastructure system disruptions. However, there is another widely used concept, *reliability*, that can be said to fit into roughly the same definition, and we want to make a distinction between vulnerability and non-reliability.

In the quantitative risk analysis literature, reliability is defined quite strictly as “the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered” (Høyland and Rausand, 1994). Reliability analysis generally models systems as being structures of components, each with a certain stochastic life length. The purpose of the analysis is typically to calculate the expected life length of the system, or if components are repaired, the probability that the system is operational at a given time. From this perspective, reliability analysis thus represents a different restriction of risk analysis than vulnerability analysis, in which the impacts of scenarios are only evaluated as whether a system is performing its purpose adequately or not (e.g., a machine or a plant manufacturing goods according to set quality standards).

The term reliability is often also applied less strictly, not least in transport research where it may refer to the stability and predictability of travel conditions such as travel times over time (see further Section 4). When used in this sense, reliability studies are focused on the upper left corner of Figure 1, that is, the impacts from relatively frequent and moderate fluctuations in travel conditions; typically, it is assumed that users know the probability distribution of travel conditions but not the realised conditions on a given day (e.g., Fosgerau and Karlström, 2010).

To distinguish vulnerability analysis from reliability analysis, in particular with regard to the road transport system, we will further restrict the focus of vulnerability analysis to mainly the lower right corner of Figure 1, that is, relatively rare

events with severe impacts. As Figure 1 also indicates, the two concepts can be considered to be overlapping, and we will not attempt to define, nor do we desire, a precise boundary between them. The relationships between the concepts of risk, reliability and vulnerability with respect to the road transport system are also discussed by for example Berdica (2002), Nicholson (2003) and Husdal (2004).

3. Experiences from road network disruptions

Before entering the field of model-based, quantitative vulnerability analysis it is important to consider what can be learnt from empirical observations of real events. To this end, we first consider two recent disruptions of road transport systems, one international with very severe impacts and one Swedish with more moderate impacts for society; it is likely that the reader will know of similar events that have occurred in her own vicinity. We then complement the picture with evidence gathered from other major and minor events.

3.1. The I-35W bridge collapse, Minneapolis, 2007

At approximately 6:05 pm on August 1 2007 the I-35W bridge in Minneapolis, Minnesota collapsed without warning into the Mississippi river. In its accident report, the National Transportation Safety Board (NTSB) identified a design flaw, in combination with ongoing repair work that put an unusually heavy load on the structure, as the likely cause of the failure. The collapse had immediate and tragic effects since thirteen people were killed and 145 people were injured (NTSB, 2008).

As the bridge carried a typical flow of 140,000 vehicles per day, the collapse meant a significant disruption of normal travel conditions. Surveys and loop detector data showed that it took several weeks for the traffic to settle into a new stable state and that people responded primarily by changing routes, departure times and destinations and possibly by consolidating trips. Public transport services experienced an increase in ridership during the disruption, but as the modal share of public transport is low in the area the effect on car traffic was limited (Zhu et al., 2010b).

A number of adjustments of the transport infrastructure were made within days after the collapse in order to better accommodate the increased traffic flows in the surrounding network. This included transforming a bus-only shoulder lane to a fourth normal lane on the parallel I-94 bridge and blocking certain on- and off-ramps. On September 18 2008 a replacement bridge was opened, while the fourth lane on the I-94 bridge was removed on October 12. Surveys and detector data show that the traffic adapted more quickly to the reopening, which was well known beforehand, than to the collapse. Somewhat paradoxically, the overall benefits

on travel times from the opening of the new bridge were more than offset by the restoration of the fourth I-94 lane to a shoulder lane (Zhu et al., 2010a).

The total societal costs of the bridge collapse are difficult to survey. On August 6 2007 the state of Minnesota was granted 250 million USD in federal emergency relief funding for clean-up, recovery and restoration (Horwath, 2007). The construction of the new bridge cost approximately 234 million USD (Lohn, 2007), while victims of the collapse were compensated by the state of Minnesota with in total 38 million USD (Lohn, 2008). Further cost components for which we have not found estimates include the emergency rescue and recovery efforts, the clean-up of water and land, and the modifications of the road infrastructure other than building the new bridge.

Soon after the collapse an assessment of the costs due to delays was made. Changes in travel time were calculated using a transport planning model system, which were then multiplied with a composite car and truck value of time of 14.19 USD/hour to obtain the delay costs. These were estimated to between 71 thousand USD and 220 thousand USD per day depending on assumptions about traveller response (Xie and Levinson, 2009). In a separate assessment the Minnesota Department of Transport estimated the traveller costs to 400 thousand USD per day, including increases in both travel time and distance. The total impacts on Minnesota's economy were estimated to 17 million USD in 2007 and 43 million USD in 2008 (State of Minnesota, 2008).

3.2. The flash flood at Ånn, Sweden, 2006

At around 6:45 pm on July 30 2006 the E14 European highway between Trondheim, Norway and Sundsvall, Sweden, was cut off west of Östersund on the Swedish side of the border. Heavy cloudbursts during the day had caused the flooding of a small stream, which eroded the ground upstream of the road. The water carried large quantities of soil, trees and debris toward the road, causing the insufficiently dimensioned road drains to choke up. Within a few hours, the pool of water that formed at the mouth of the drains caused the road structure to collapse and about 30 meters of the road was completely washed away. A railway going along the downstream side of the road was also demolished by the unleashed flood (Länstidningen Östersund, 2006b).

The road is an important connection between Sweden and Norway with a daily flow of about 1000–2000 vehicles, and long queues were built up before traffic was redirected along alternative routes. People living on one side of the incident area and working on the other were forced to make a daily detour of more than 200 kilometers. Tracked vehicles were called in to transport people past the area. Swedish residents living west of the area were unable to reach medical care in Sweden and were referred to Norway. After two days a small temporary parallel road was built next to the incident area. The road only allowed vehicles to pass in one direction

at a time, and could only carry vehicles without trailers and weights below four tonnes. Ambulances were now able to reach people beyond the area (Jämtlands läns landsting, 2006; Länstidningen Östersund, 2006a,d; Vägverket, 2006a).

On August 11, twelve days after the event, the E14 was reopened after repairs. Initially, one lane was kept closed and the speed limit of the road was reduced because of ongoing work. The old drain pipes were replaced with new pipes with a larger dimension to reduce the risk of similar events occurring again. The cost of the repairs was estimated to about eight million SEK (about 1.2 million USD) for the road and a similar amount for the railway. The regional train operator estimated that loss of revenues, substitution of traffic with bus and taxi, repair costs for a damaged train and bad-will effects led to a cost of 1.5 million SEK. No calculation of the societal costs due to increased travel times appears to have been presented (Länstidningen Östersund, 2006c; Länstrafiken i Jämtlands Län, 2007; Vägverket, 2006b; Vägverket Produktion, 2006).

3.3. Disruption causes and impacts

Many types of scenarios can potentially cause severe disturbances in the road transport system. To begin with, some events are caused by the traffic itself, in the form of car accidents or exceptional congestion due to large public events. Some incidents are caused by external accidents such as industrial leakages or ships ramming bridges (e.g., the ramming of Essingeleden in Stockholm, Sweden, October 14 2005); others are caused by technical failures of the road structure, bridges, etc., due to wear and tear or faulty construction (e.g., the I-35W bridge collapse described above). Still others are caused by adverse meteorological, hydrological or geological conditions, such as flash floods, snow storms, landslides and earthquakes, that either disrupt the road network or obstruct the traffic (e.g., the Northridge earthquake 1994). Furthermore, we cannot ignore the reality of intentional attacks on the transport system, for example as a means to inflict disorder and panic to the society or to delay the police after a robbery (e.g., the train bombings in Madrid 2004).

Berdica (2000) studies the most common causes of complete road closures in the Swedish road network, which are found to be, in descending order, road works, floods, traffic accidents, snow, storm-related incidents, hazardous goods accidents, physical collapses, thaw weakening damage, and bridge openings.

Just like the causes, the effects of road network disruptions can be multifaceted. First and most severely, some events, for instance car accidents and infrastructural collapses, may cause injuries and fatalities directly. There may also be service disturbances that will threaten life and health indirectly. One such service is the ability for people to receive emergency medical care. In a worst-case scenario an incident may cut off all possibilities to reach a hospital or for an ambulance to reach the person in need; in other cases, the alternative routes may be too long.

Assistance from the police and the fire department also belong to this category.

Second, there are the less acute consequences, i.e., disturbances that are not a threat to life and health in the short run, but may cause anything from substantial economic and social strains to mere nuisances. For people, this includes impaired abilities to get to work in time, to drop off and pick up children from daycare and school, to do the shopping, to attend leisure activities, and so on. For companies, the impacts include delayed deliveries and supplies (with possible ripple effects), loss of manpower and customers, increased freight costs, delayed or cancelled business meetings, etc. All these impacts are associated with societal costs, although it may vary from case to case, through insurance, settlements, court rulings etc., which parties actually end up paying for the effects.

Third, there may be large costs associated with remedies and restoration of the transport system to a fully operational state. These costs may range from relatively low, for example when towing away crashed vehicles or providing emergency rerouting, to very high, such as when rebuilding or replacing a collapsed bridge or road segment.

Regarding the traffic responses to unplanned transport network disruptions, empirical evidence tells us that such events are generally followed by a time—on the order of days or weeks—of uncertainty, learning and adaptation for the travelers. If the degradation is long-lasting, the traffic eventually approaches a new equilibrium-like state, where travelers have received sufficient information about the new travel conditions and adjusted their travel decisions accordingly. Observations are fairly consistent in that the most common responses by individuals are changes in departure time and route choice. To a lesser extent people cancel or consolidate (mainly non-work) trips, whereas people are relatively reluctant to change travel mode (Wesemann et al., 1996; Giuliano and Golob, 1998; Hunt et al., 2002; Cairns et al., 2002; Clegg, 2007; Zhu et al., 2010b).

In many areas, for example in USA (Transportation Research Board, 2008) and the UK (Department for Transport, 2004), *climate change* is predicted to increase the strains on the road infrastructure. Recently, a commission investigating the consequences for Sweden of the anticipated climate changes concluded that the risk for floods, landslides and erosion will increase in many areas, affecting houses, railways and roads (Klimat- och sårbarhetsutredningen, 2007). For the road network the costs associated with these damages between the years 2010 and 2100 are estimated to 10–20 billion SEK (ca. 1.5–3 billion USD). The commission suggests that adaptations of the transport infrastructure to a changed climate should be made a part of the national transport policy goals, and that resources should be earmarked for this purpose. Furthermore, the risks for the road and railway networks should be surveyed and countermeasures taken.

4. Quantitative vulnerability analysis: A review

Traditionally, transport policy and planning has been focused on the performance of the transport system under typical demand and supply conditions. In recent years, however, it has been increasingly recognized that variations from the normal state can cause considerable reductions in efficiency. The ability of the transport system including its users to handle fluctuations in operating conditions has become known as transport or travel reliability. Studies in this field usually consider some aspect of the transport system such as link capacities, travel demand or travel times to vary randomly according to some specified distribution and assess the user costs or the impacts on system performance from this variability.

One of the earliest and simplest measures of transport network reliability is terminal or connectivity reliability, which is the probability that there is still a connection between a pair of nodes in the network when one or more links are closed (e.g., Wakabayashi and Iida, 1992; Bell and Iida, 1997). More refined reliability measures that have been introduced include travel time reliability, i.e., the probability that a trip can be completed within a specified time interval (e.g., Yang et al., 2000; Clark and Watling, 2005) and capacity reliability, defined as the probability that a network can accommodate a specified level of travel demand (e.g., Yang et al., 2000; Chen et al., 2002). The travellers' costs of travel time uncertainty and variability have been studied both theoretically and empirically by for example Noland and Small (1995), Bates et al. (2001), Noland and Polak (2002) and Fosgerau and Karlström (2010). For fuller overviews of the subject see Iida and Bell (2003) and Watling (2008).

The field of transport network vulnerability (and robustness, which may be seen as the converse of vulnerability) focuses mainly on larger, unexpected disruptions rather than the day-to-day variability in travel conditions and has received growing attention as well. Early contributions include Garrison (1960) who used graph-theoretical concepts to analyze the structure of the US Interstate Highway system and found that the failure of a link in the network could lead to long detours. In the field of operations research, algorithms for finding the most important (or "vital") nodes and links in networks were also developed early (e.g., Ratliff et al., 1975; Ball et al., 1989). The goal of these mathematical programs is typically to find the node or link that when removed increases the length of the shortest path or reduces the maximum flow between a given origin node and destination node the most.

The current research interest in transport vulnerability commenced in the early 2000s, largely as part of a broader focus on critical infrastructure protection. Several recent natural disasters, including the earthquakes in Los Angeles 1994 and Kobe 1995, and terrorist attacks, most prominently the events on September 11 2001, raised awareness that society is vulnerable to disruptions in these infrastructure systems. It was recognized by some researchers that the methods from the transport reliability field were inadequate for assessing the consequences of se-

vere, albeit seemingly unlikely, disruptions of the road transport system and that new approaches were necessary (Berdica, 2002; D'Este and Taylor, 2003; Nicholson, 2003).

As requested by these authors, the vulnerability research has embraced a rich exploration of approaches, metrics and models. The applied literature can be broadly classified with respect to the kind and range of disruption scenarios that are studied. The following categories are largely based on the overview of the more general field of infrastructure vulnerability analysis given by Murray et al. (2008), who also discuss the benefits and disadvantages of the different approaches in depth.

A first category of studies have focused on one or a few specific scenarios. Notably, several authors have assessed the economic impacts of earthquakes disrupting the road network using integrated transport network and multiregional trade models (Cho et al., 2001; Kim et al., 2002; Ham et al., 2005; Tatano and Tsuchiya, 2008). Suarez et al. (2005) study the impacts of flooding and climate change on the urban transport system of Boston Metro Area, USA, using a four-stage (i.e., trip generation, destination choice, mode choice and route choice) transport modeling system. Similar approaches are used by Berdica and Mattsson (2007) to evaluate the societal impacts of bridge closures in Stockholm, Sweden, and Taylor (2008) for a tunnel blockage in Adelaide, Australia.

A second category of studies, descendant from the work of for example Ratliff et al. (1975), use mathematical modeling and optimization techniques to identify worst-case scenarios, or best responses to such scenarios. Matisziw and Murray (2009) use an integer programming formulation to identify the most severe disruptions of a given number of links in the truck transport network of Ohio, USA. Bell et al. (2008) integrate a macroscopic traffic assignment model in a game-theoretic framework to determine routing strategies for the shipment of VIPs in London, UK under the risk of antagonistic attacks.

A third category of studies consider a full range of scenarios, through either exhaustive calculation or Monte Carlo simulation. Dalziell and Nicholson (2001) present what may perhaps be called the only complete road network vulnerability analysis and management study in the literature. In the study, focused on the Central North Island road network of New Zealand, the authors identify a range of plausible disruption hazards (including snow and ice, ash fall, earthquakes and car crashes) along with a frequency distribution of closure durations for each hazard. Specific scenarios with different closure durations are then generated through Monte Carlo simulation, and the impacts including both restoration work and the economic losses of the travellers are evaluated. Following this assessment a cost-benefit analysis is performed to identify the most efficient options for mitigating the identified vulnerabilities.

Several authors have performed full range studies of single link failures in road networks. Taylor et al. (2006) analyze the Australian road network at different

levels, using various measures of diminished accessibility to evaluate the impacts of link failures. Sohn (2006) proposes an accessibility index that integrates road distance and traffic volumes and uses it to assess the importance of highway links in Maryland, USA, under flood damage. Knoop et al. (2008) use macroscopic traffic simulation to evaluate the impacts of link blockings in Rotterdam, the Netherlands. In a study of the Swiss road network, Erath et al. (2009) handle the computational challenges associated with full range analyses by restricting the calculations to a subnetwork surrounding each disrupted link. We may note, finally, that Papers I–V in the present thesis also belong to this category.

As Murray et al. (2008) note, the different approaches to vulnerability analysis all have their merits and shortcomings. With a scenario-specific assessment, it is possible to use sophisticated quantitative models that can capture many features of the particular scenario and system. There is a risk, however, that other relevant and possibly more severe scenarios are overlooked, which could lead to a biased picture of the situation. With optimization approaches, it is possible to identify worst-case scenarios, which are undoubtedly of great value, without exhaustive examination of all possible scenarios. Again, there is a danger that other severe scenarios may be overlooked, and also that the properties of the mathematical program to a large extent determines what vulnerability metrics are feasible to use.

Finally, with a full range approach, one gets a comprehensive picture of the vulnerability of the network, including worst-case scenarios as well as distributions across users and regions. It is also possible to draw general conclusions about the factors underlying vulnerability. This comes at the price of extensive calculations, which may require simplified models and vulnerability metrics to be feasible. Such simplifications, in turn, may mean that important features of the system and individual scenarios are overlooked.

In addition to these studies, a number of authors have proposed indices to evaluate road network vulnerability and quantify link and node importance, although they have only been applied to test networks. Thus, Murray-Tuite and Mahmassani (2004) propose a vulnerability index that accounts for traffic flow, link capacities, travel times and the availability of alternative routes. Scott et al. (2006) propose a Network Robustness Index to identify important links in highway networks, which is defined as the increase in vehicle travel time that is incurred when the link is closed. The index is generalized by Sullivan et al. (2010) who note that complete link closures are only one of many possible kinds of disruption scenarios and argue that the level of capacity reduction should be considered that gives the most stable importance ranking of different links. Another similar importance measure, based on the inverse of travel cost, is defined by Qiang and Nagurney (2008).

Some papers develop and investigate the models that are used to calculate the impacts of network disruptions; Paper VI here belongs to this category. Chen et al. (2007) propose the use of a combined travel demand model incorporating trip generation, destination choice, mode choice, and route choice to assess the long-term

equilibrium effects of a closure of one or more links. The consequences are calculated as the decrease of a utility-based accessibility measure. He et al. (2009) model the day-to-day development of traffic flows after unplanned network disruptions based on past experiences and beliefs about the future conditions. Notably, Berdica et al. (2003) study the consequences of the same incident scenario with three different models (on the macro, meso and microscopic scales, respectively) and find that the results differ significantly. The authors remark that “although a model may be well calibrated for normal conditions, there is no guarantee that it will predict abnormal conditions correctly”.

5. Perspectives of vulnerability analysis

As illustrated in Figure 2 an infrastructure system such as the road transport system can be seen as consisting of three parts: First, there is the technical and physical infrastructure including roads, traffic signals, vehicles etc. Second, there are the direct and indirect users of the technology, i.e., travellers, transporters and society in general. Third, there are the planning and operating authorities responsible for providing and maintaining the technology and the infrastructure in order to serve society under given regulations and budget restrictions. In economic terms the first (technology) and second (users) parts can be regarded as the supply and demand sides of the system, respectively, while the third part (authorities) regulates the two sides and their interactions.

It should be noted that for planning and operating authorities the defined strategic goals are typically centered on the users and the society, such as efficiency, accessibility, reliability, safety, equality and regional development. Meanwhile, the available decision variables are mainly concentrated to the technological supply side, including new road projects, maintenance, traffic signal settings, speed limits and road tolls.

5.1. Importance and criticality

This trisecting systems model suggests two main perspectives on vulnerability (or any other issue) from the point of the responsible authorities. The first perspective focuses on the *technological* side of the system. For a given component or group of components, here collectively called an *element*, we may ask: What is the probability that the element is disrupted (in a certain way, under certain conditions) and what would be the welfare effects for society? Extending the vulnerability analysis to vulnerability management, we may further ask: How would this risk be affected if preventive, mitigative or restorative investments were to be made?

Following Nicholson and Du (1994), in this thesis the impact of a disruption of a given element is called the *importance* of the element. Many other terms have been used in different fields for the same concept, including “criticality” (Taylor

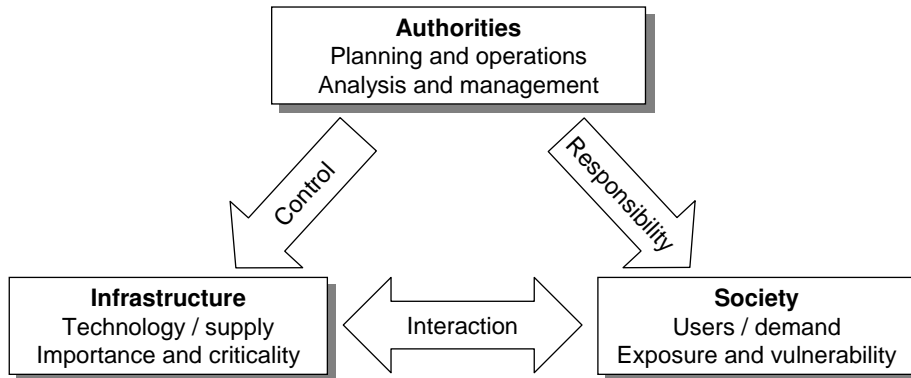


Figure 2: A simple trisecting model of an infrastructure system. The second line in each box represents the typical role of each part; the third line represents their roles in vulnerability analysis.

and D’Este, 2004; Taylor et al., 2006), “vitality” (Ratliff et al., 1975; Ball et al., 1989), “vulnerability” (Murray-Tuite and Mahmassani, 2004; Knoop et al., 2008), “significance” (Sohn, 2006), “delta centrality” and “information centrality” (Latora and Marchiori, 2007). In any case, it is the notion rather than the name that is of interest here. The main purpose behind the importance measure is to compare and rank different elements. This allows, for example, the identification of hot spots in the infrastructure system where disruptions would be particularly severe. Disruptions of such elements represent worst-case scenarios and the elements can also be considered potential targets for *antagonistic attacks* on the system.

Identifying important elements means that targeted measures can be taken to reduce the risk (i.e., the probability and/or consequences) of disruptions in those locations. More generally, the importance of each element combined with the probability of the element being disrupted is useful when allocating resources to reduce the overall vulnerability of the society. Again following Nicholson and Du (1994) the combination of importance and disruption probability, i.e., the overall disruption risk associated with the element is called the *criticality* of the element. Importance can thus be expressed as conditional criticality.

In practice, of course, the location (and hence the network element involved) is only one of many dimensions in which the characteristics of an infrastructure disruption scenario can vary. Other factors that will influence the impact and probability of a disruption include the time of occurrence (time of day, weekday, season etc.), the duration, the degree of performance reduction of the affected components, and the intermediate countermeasures taken, to name just a few. The concept of element importance thus necessarily entails making some explicit or implicit assumptions about these other scenario dimensions, in a way that makes comparisons among elements meaningful.

The approach adopted in this thesis is to calculate the importance conditional

on certain values for the other dimensions. Some of the scenario dimensions can be handled explicitly by introducing parameters controlling them. This is done in Papers II–V for the duration of the disruption. Thus, we can study element importance for, say, a 1-hour or a 24-hour disruption, which may lead to different element rankings. Other scenario dimensions may be handled more implicitly in the impact model that is used. In this thesis this includes the time of occurrence (the travel demand data we use represents an annual daily average vehicles per hour) and degree of capacity reduction (we only consider complete link closures). Also, in the impact model used in Paper I the disruption duration has no impact on importance rankings and is left implicit.

5.2. Vulnerability and exposure

The second perspective on vulnerability from the authorities' point of view is to focus on the *social* side of the system. For a given individual we may ask: Under various conceivable disruption scenarios, how would the individual be affected and what is the probability that each scenario will occur? For example, we may also ask: What would be the impacts of the worst-case plausible scenario, and what are the long-run expected impacts of system disruptions? Extending into vulnerability management, how would these risks be affected by various preventive, mitigative or restorative investments?

The impact for a single individual, or user, under a certain disruption scenario is referred to in this thesis as the *exposure* of the user to that scenario; to the best of our knowledge, the term was first used in this setting in Paper I. Combining the exposure with the likelihood of the scenario occurring gives the *vulnerability* of the user to that scenario. Exposure can thus be seen as conditional vulnerability from a social perspective. It should be noted that Taylor and D'Este (2004) and Taylor et al. (2006) use the term “vulnerability” for essentially the same concept as exposure.

The idea behind the exposure concept is to study and compare the situation for different individuals depending on any socioeconomic variables of interest, such as gender, age, income or residential location. This makes it possible to identify groups of individuals that would be particularly severely affected by a certain disruption scenario and, more generally, the distributive and equity effects of the scenario beside the overall impact. To promote equity and regional development, for example, it may be desirable for authorities to direct investments and actions aimed at reducing vulnerability so as to particularly benefit certain disadvantaged groups.

As noted above, the space of conceivable disruption scenarios for an infrastructure system can be enormous or infinite, and it may be of interest to consider some aggregate measures of user exposure across a wide range of scenarios. One obvious such aggregation approach is to consider the worst case along one or several dimensions of the scenarios. For example, we can study the worst possible

impacts of a closure of a single link in the road network given a fixed closure duration across all links. The *worst-case exposure* thus captures the most severe impact for the user that a disruption of particular kind can have, regardless of the probability that this scenario will occur. Such an analysis can be useful for emergency preparedness and when scenario probabilities are highly uncertain, which is often the case.

If each conceived disruption scenario is associated with a frequency or probability of occurrence within some time interval of interest, another possible aggregation approach is to multiply probability and impact and consider the statistically expected vulnerability along one or several dimensions of the scenarios. Determining these probabilities, however, is an inherently difficult problem. A somewhat more manageable task, perhaps, is to assess the *relative* probabilities of different scenarios. This means that probabilities can be normalized across all considered scenarios to sum to 1. We refer to this expected conditional vulnerability as *expected exposure*. With this measure it is possible to study how vulnerability will tend to be distributed among individuals in the long run. For example, we may study the expected exposure to single link closures given a fixed closure duration across all links.

6. A formal framework for vulnerability measures

The concepts of element importance and user exposure can be defined more formally in a way that highlights the relationship between the two perspectives and facilitates the development of practical importance and exposure measures. At the heart of the framework are an individual, denoted n , and an infrastructure disruption scenario, denoted σ . A disruption scenario is here defined as a vector or point in a N_Ω -dimensional space Ω , where each dimension represents a relevant aspect of the disruption, such as the element involved (i.e., the set of links and nodes), the duration, the time of occurrence, the levels of capacity reductions, etc. For convenience we assume that each dimension of the scenarios is represented by a finite or infinite subset of the real numbers \mathfrak{R} , so that Ω can be represented as a subset of the real-valued set of vectors \mathfrak{R}^{N_Ω} . With each disruption scenario σ we further associate a “null” scenario $\sigma_0(\sigma) \in \Omega$ that represents the baseline, normal level of operations during the time of the disruption had it not occurred, and against which the impact of the disruption is assessed.

In reality, of course, one can observe either some disruption σ or the baseline situation $\sigma_0(\sigma)$, but never both, which makes the analysis of a counterfactual nature. If σ is observed one can make assumptions about $\sigma_0(\sigma)$ based on evidence from past similar situations (say, the typical travel conditions in the region during wintertime peak hours). In model-based analysis, on the other hand, it is possible to analyze the system both in the disrupted and the non-disrupted state and thereby

assess the disruption impacts. What models and measures that are suitable to use in a given analysis depends on the conditions and the behaviour of the users in both the disruption scenario and the null scenario.

Exposure and importance analysis involves comparing and summing the various aspects of the disruption impacts for different users under different scenarios. The impacts must therefore be expressed in units such that interpersonal comparisons and summations are meaningful. For many reasons, not least in cost-benefit analyses of vulnerability-reducing investments, it is desirable to express the disruption impacts in economic terms. This allows prevention, repair and restoration costs to be added and compared to other impacts, such as delayed goods deliveries and reduced accessibility to societal services in the case of the road transport system. For example, contractors may be given a bonus for every day ahead of normal schedule functionality is restored, as was done after the Northridge earthquake in 1994 (Wesemann et al., 1996) and the collapse of the I-35W bridge in 2007 (Xie and Levinson, 2009). The size of the bonus should be proportional to economic losses avoided by the early restoration.

With these aims it is reasonable to adopt a *micro-economic* approach and view users (i.e., individuals, businesses etc.) as economic agents interacting with each other and the infrastructure. The individual is thus seen as a consumer of goods, activities, services and—particularly for the transport system—travel. The micro-economic framework postulates that individuals make decisions in order to maximize their obtained *utility*, while businesses or firms seek to maximize their profits, under the prevailing circumstances. Within this framework the theoretical and empirical research challenge lies in properly capturing and specifying the factors that determine the utility or profit gained under different outcomes (e.g., Mas-Colell et al., 1995).

In our setting, the highest utility that the user can obtain under the circumstances represented by scenario σ is denoted $U_n(\sigma)$, and the impact of a network disruption is captured by comparing $U_n(\sigma)$ and $U_n(\sigma_0(\sigma))$. Within the micro-economic consumer models the user is typically subject to monetary budget constraints, such as the available earned and unearned income. This means that a monetary measure of the utility change $U_n(\sigma) - U_n(\sigma_0(\sigma))$ can be defined as the increase in the available budget that is required to restore the utility, indirectly through the possibility of increased consumption, to the baseline level $U_n(\sigma_0(\sigma))$. This amount is known as the *compensating variation*, or CV for short, and represents the smallest amount that the user should be willing to accept as compensation for the disruption (or in the case of an improvement, the largest amount that the user should be willing to pay for it) (Mas-Colell et al., 1995). We will use the compensating variation as our formal measure of the impact of a disruption for individuals. For individual n and disruption scenario σ we denote this quantity $\Delta C_n(\sigma)$. The framework is illustrated in Figure 3.

A transport network disruption can cause a difference, most likely a reduction,

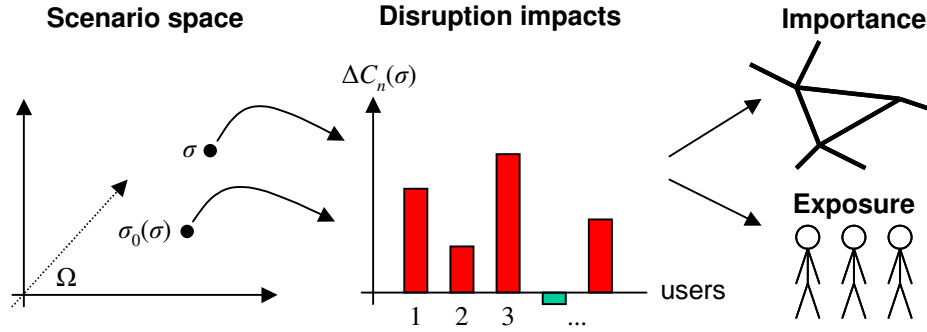


Figure 3: An illustration of the framework for vulnerability analysis: With each disruption scenario σ and corresponding null scenario $\sigma_0(\sigma)$ is associated an impact for each user n , evaluated as the user's monetary compensating variation for the difference in utility between the two scenarios, $\Delta C_n(\sigma)$. The impacts are aggregated to yield measures of element importance and user exposure.

in an individual's obtained utility compared to the null scenario for a number of reasons. A component that affects people's accessibility to critical societal services and is known to be vital for choices related to travel and activity participation is *travel time*, and network disruptions often lead to increased travel times for travellers that would normally use the disrupted element or nearby roads indirectly affected by congestion. Beside the possible discomfort of spending an unusually long time travelling, an increase in travel time means that the user will reach (or be reached by) societal services later, or must sacrifice time from other activities that may be more desirable than travel. With appropriate *information* the user may counteract this utility loss to some extent by cancelling the trip, travelling to other destinations or in other ways adjusting her plans. Paper VI proposes an activity-based model to capture some of these utility losses, for work trips in particular, under various levels of available information and schedule flexibility; see further Section 10.

6.1. User exposure

Within this formal framework the exposure of user n to scenario σ is simply

$$E(n | \sigma) = \Delta C_n(\sigma). \quad (1)$$

To formalize the *worst-case* exposure of individual n , we partition the dimensions of the scenario space Ω into two subspaces, denoted Ω_1 and Ω_2 , such that a scenario $\sigma \in \Omega$ can be written as $\sigma = (\sigma_1, \sigma_2)$, where $\sigma_1 \in \Omega_1$ and $\sigma_2 \in \Omega_2$. Without loss of generality we assume that we are interested in the worst possible impacts along the dimensions in Ω_2 , while the dimensions in Ω_1 are kept fixed at a

certain point σ_1 . The worst-case exposure of n with respect to Ω_2 is then

$$E^{\text{wc}}(n | \sigma_1, \Omega_2) = \max_{\sigma_2 \in \Omega_2} \Delta C_n(\sigma_1, \sigma_2), \quad (2)$$

assuming for simplicity that a maximum always exists. As an example, if we consider the worst-case impact of a single link closure in a road network, Ω_2 may represent the different links in the road network while Ω_1 may represent different possible closure durations, times of occurrence etc., of which σ_1 is a particular case.

To formalize the *expected* exposure of individual n , we require that every considered disruption scenario σ is associated with a probability of occurrence normalized to 1 across all scenarios. More precisely, we should allow some dimensions of the scenario space Ω to be infinite (such as all possible closure durations), whereas others may be finite (such as all links in the network), which means that probabilities should be represented by a multivariate discrete-continuous distribution function $F_\Omega(x) = P(\sigma \leq x)$ where $\sigma \leq x$ is to be interpreted element-wise. Given a particular value x_1 for the dimensions Ω_1 one can derive the conditional distribution function $F_{\Omega_2}(x_2 | x_1) = P(\sigma_2 \leq x_2 | \sigma_1 = x_1)$. The expected exposure across all scenarios given σ_1 can then be written as

$$E^{\text{exp}}(n | \sigma_1, \Omega_2) = \int_{\Omega_2} \Delta C_n(\sigma_1, \sigma_2) dF_{\Omega_2}(\sigma_2 | \sigma_1). \quad (3)$$

6.2. Aggregate group exposure

Rather than focusing on single individuals, we may more often be interested in the exposure of aggregate *groups* of individuals. The grouping may be based on some socioeconomic variables of interest, such as income, gender or residential location. The *total exposure* of a group $g = \{n_1, \dots, n_{N_g}\}$, where N_g is the number of individuals in the group, to scenario σ is then

$$TE(g | \sigma) = \sum_{n \in g} \Delta C_n(\sigma). \quad (4)$$

This represents the total impact of the disruption in economic terms for the group. Meanwhile, the (mean) *user exposure* of the group to scenario σ is simply the total exposure divided by the number of individuals, i.e.,

$$UE(g | \sigma) = \frac{1}{N_g} \sum_{n \in g} \Delta C_n(\sigma). \quad (5)$$

Worst-case and expected exposure measures can be defined analogously for a group, in total or per user on average, as for a single user. We include the formal

expressions here for completeness; the worst-case and expected total exposure of the group are

$$TE^{\text{wc}}(g | \sigma_1, \Omega_2) = \max_{\sigma_2 \in \Omega_2} TE(g | \sigma_1, \sigma_2), \quad (6)$$

$$TE^{\text{exp}}(g | \sigma_1, \Omega_2) = \int_{\Omega_2} TE(g | \sigma_1, \sigma_2) dF_{\Omega_2}(\sigma_2 | \sigma_1), \quad (7)$$

and the worst-case and expected user exposure are

$$UE^{\text{wc}}(g | \sigma_1, \Omega_2) = \max_{\sigma_2 \in \Omega_2} UE(g | \sigma_1, \sigma_2), \quad (8)$$

$$UE^{\text{exp}}(g | \sigma_1, \Omega_2) = \int_{\Omega_2} UE(g | \sigma_1, \sigma_2) dF_{\Omega_2}(\sigma_2 | \sigma_1). \quad (9)$$

6.3. Element importance

As noted above, the road network element involved is only one of many dimensions in which the characteristics of an infrastructure disruption scenario can vary, and our approach to measure the importance of the element is to calculate the total impact of a certain disruption scenario involving the element, conditional on certain values for the other dimensions. Separating the element, denoted e , from the values for the other dimensions, jointly denoted y , the scenario can be written as $\sigma = (y, e)$. The importance of element e can be defined with respect to a particular group of users g as

$$I(e | y, g) = \sum_{n \in g} \Delta C_n(y, e). \quad (10)$$

By comparing formulas (4) and (10) it may be observed that the importance of element e to group g is identical to the total exposure of group g to the disruption scenario involving element e . In this thesis we will be primarily interested in the case where the group represents the *entire society*, i.e., in the overall importance of elements, in which case the group index will be omitted.

7. From formal to practical measures

In order to conform to the data and models employed in the studies of the road transport system, the practical importance and exposure measures used in Papers I–V are simplified, and superficially quite different, versions of the formal measures above. To begin with the data, the analysis is based on a network representation of the road transport system with nodes representing intersections or dead ends, and directed links representing road segments between the intersections. Each link k has, among other variables, an associated fixed length l_k and a travel time t_k that may be a function of the link flow f_k (it is assumed fixed in our studies, however).

To the network special origin/destination (OD) nodes, or *demand nodes*, are also connected, representing possible locations where trips enter and leave the road network. All OD nodes have associated coordinates that allow them to be partitioned into geographical regions. Associated with the demand nodes are OD *demand matrices*, which contain the number of trips of a certain type (such as work trips) being made during a certain time period (such as the annual average daily travel demand) between each OD node pair under normal conditions.

It should be noted here that the data concern *trips*, while our formal measures concern *individuals*. Moving from users to trips could have an influence on the analysis if a single user makes multiple trips and the impacts of a disruption are not additive across trips (as the model in Paper VI suggests). It could also affect exposure comparisons between groups if the number of trips made per user varies between groups. In this thesis, however, we will not delve further into these issues and will often, somewhat imprecisely, use the term user (as in user exposure) even though the units of analysis will be trips.

Furthermore, the impact models used in Papers I and II–V are adapted to the level of detail in the analysis that the available data allows, which is relatively coarse. First of all we assume that disruption scenarios consist of *complete closures* of one or several links for a certain duration τ , which is typically assumed to be a few days at most. During this time the travel demand is assumed to be inelastic to the disruption, so that all trips between each OD pair that would be made normally will also be made between the same OD pair given the disruption, although possibly postponed until the normal situation is restored. The travel demand per unit time between each OD pair (i, j) , denoted x_{ij} , is assumed to be constant during the disruption and consistent with the OD demand matrix used.

Finally, in Papers I–V the compensating variation for each user, or actually trip, related to the disruption is assumed to be proportional to the increase in travel time or duration of postponement of the trip, collectively called the *delay* of the trip. People thus choose routes and departure times in order to minimize the travel time. Moreover, the proportionality constant, i.e., the value of time, is assumed to be the same for all trips and individuals, so that a delay of a certain length is considered equally bad regardless of who is affected. The value of time, being just a common proportionality constant for all trips, can thus be omitted in relative analyses. Interpreted differently, we ignore the fact that different users on different trips may find the disruption more or less costly and focus on the underlying, more tangible delays. This is problemized in Paper VI and Section 10 below, where we derive functional forms for the relationship between journey delays and costs.

These assumptions mean that a disruption scenario can essentially be described with only two parameters: The element (the link or group of links) being closed, e , and (in Papers II–V) the closure duration, τ . Another consequence is that a trip is also characterized by two factors: the OD pair (i, j) between which the trip takes place and (in Papers II–V) the departure time relative to the start and end of the

disruption.

The total delay compared to the baseline situation (the null scenario with all links fully operational) for all trips between i and j during the disruption given scenario $\sigma = (\tau, e)$ is denoted $\Delta T_{ij}^e(\tau)$. The overall importance of element e is thus obtained by summing $\Delta T_{ij}^e(\tau)$ across all OD pairs (compare with (10)),

$$I(e | \tau) = \sum_i \sum_j \Delta T_{ij}^e(\tau). \quad (11)$$

In Papers I–III and V we study spatial disparities and often partition the trips based on the regions where they start, specifically municipalities or counties. Let $i \in r$ mean that OD node i is located within region r . The total exposure of region r to scenario (τ, e) is then (compare with (4))

$$TE(r | \tau, e) = \sum_{i \in r} \sum_j \Delta T_{ij}^e(\tau). \quad (12)$$

The total travel demand between i and j during the duration of the disruption is $x_{ij}\tau$, and the user exposure of the region to scenario (τ, e) is (compare with (5))

$$UE(r | \tau, e) = \frac{\sum_{i \in r} \sum_j \Delta T_{ij}^e(\tau)}{\sum_{i \in r} \sum_j x_{ij}\tau}. \quad (13)$$

The *worst-case* total and user exposure for a given closure duration τ are found by taking the maximum of $TE(r | \tau, e)$ and $UE(r | \tau, e)$ across the set of all considered elements \mathcal{E} , which corresponds to the general set Ω_2 in the formal framework. Similarly, the *expected* total and user exposure are found by associating each element with a normalized closure probability $p_e(\tau)$ and calculating the expected impact across all considered elements as a weighted sum, corresponding to the general integrals in the formal framework. Thus, the worst-case and expected user exposure of region r are

$$UE^{\text{wc}}(r | \tau, \mathcal{E}) = \max_{e \in \mathcal{E}} UE(r | e, \tau) \quad (14)$$

and

$$UE^{\text{exp}}(r | \tau, \mathcal{E}) = \sum_{e \in \mathcal{E}} p_e(\tau) UE(r | e, \tau), \quad (15)$$

with analogous expressions for the worst-case and expected total exposure (compare with (6)–(9)).

8. Importance and exposure measures in the thesis

Throughout Papers I–V a large number of variations on the two main themes importance and exposure are presented. In actuality the number of different measures introduced is smaller than the numbers of formulas and names would suggest. This is in part an effect of the natural work process, which means that later work has sought to expand and improve upon earlier work. In part it is an effect of the need to appropriately label measures before putting them in relation to each other, which means that the same measure may have different labels in different papers depending on the points of departure. Here we will summarize the various introduced measures and labels and relate them to each other.

8.1. Importance measures

Paper I, the earliest paper, proposes three importance measures: (i) “global”, (ii) “demand-weighted” and (iii) “unsatisfied demand-related” importance. The two first measures are expressed in terms of changes in *generalized travel cost* rather than travel time, which essentially corresponds to the compensating variation of the formal framework here; in the practical calculations in the paper, travel time is used for generalized travel cost. The “global” importance measure uses OD pairs rather than trips as the smallest units of analysis. Thus, it focuses more on the potential to travel from anywhere to anywhere and less on the actual travel patterns. This measure is not used in any of the other papers.

The “demand-weighted” importance measure corresponds essentially to the practical importance measure (11) above. A small difference is that the measure in Paper I expresses the average impact per trip rather than the total impact for all trips; this does not affect relative comparisons between links in the same network. A larger difference is that trips that cannot be completed during a link closure (i.e., unsatisfied demand) are not included in the measure, and links of which closures cause unsatisfied demand, called *cut links* in the thesis, are handled separately with the “unsatisfied demand-related” measure. In Papers II–V this division into two importance measures is eliminated by introducing an explicit closure duration, assuming that unsatisfied trips are postponed until after the closure and expressing all impacts in terms of delays.

Paper II introduces the concept of (mean) “regional” importance. This is simply the mean importance of the links, more precisely of every road segment of unit length, located within a certain geographical region. With the used model the impact of a link disruption is the same regardless of where along the link it occurs. Therefore the unweighted mean importance across every unit length road segment is equivalent to the mean importance across every link k weighted by its length l_k .

Paper III contains three named importance measures: (i) “efficiency”, (ii) “equity” and (iii) “equity-weighted” importance. The first measure is identical to the basic importance measure (11) here. The “efficiency” label is added in Paper III because the measure only considers the overall impact of a disruption regardless of how it is distributed among users. The “equity” importance measure, meanwhile, captures only the skewness of the distribution of impacts among users. This measure is not intended as a practical importance measure on its own but is combined with the “efficiency” importance measure to form the third, “equity-weighted” importance measure. With this measure links are considered more important if a given overall impact is more unevenly distributed among users, or put differently, if the disparity in user exposure to the closure of the link is greater.

Paper IV is focused on links’ roles as rerouting alternatives when other links are closed and contains four named link importance measures: (i) “flow-based efficiency”, (ii) “impact-based efficiency”, (iii) “flow-based redundancy” and (iv) “impact-based redundancy” importance. The “flow-based efficiency” importance measure is simply the normal flow across the link. It is considered a measure of importance in this paper because it captures how many users rely on the link for their travel. The “impact-based efficiency” importance measure, just like the “efficiency” importance measure of Paper III, is identical to the basic importance measure (11) here; the prefix “impact-based” is added to distinguish it from the flow-based measure.

A link’s importance as rerouting alternative for other links is called “redundancy” importance in Paper IV and represents a quite different form of importance from the other measures in the thesis. “Flow-based redundancy” importance parallels “flow-based efficiency” importance by considering the flow that is rerouted to the link when other links are closed, whereas “impact-based redundancy” importance parallels “impact-based efficiency” importance and considers the impact that is avoided by the availability of the link as rerouting alternative.

Paper V, finally, presents a study of “cell” importance, where a cell is an area of a specific shape, size and location that is part of larger grid of cells covering the study area. In the analysis a cell is equivalent to the element consisting of all links intersecting the cell area (fully or partially). Thus, “cell” importance is a special case of the basic element importance measure (11) in Section 7.

8.2. Exposure measures

Paper I studies in total six different measures of regional exposure to single link closures. That is, users are partitioned into groups based on the geographical regions (more specifically, municipalities) in which their trips originate. All six measures, of which three represent worst-case exposure and three represent expected,

here called “average-case”, exposure, actually capture the mean *user* exposure of the region, rather than the *total* exposure. The three variations of each measure arise in the same way as the three different measures of link importance proposed in the paper: The “global” exposure measure uses OD pairs as the units of analysis, the “demand-weighted” exposure measure is based on actual travel demand just like the basic user exposure measure (13) here, whereas the “unsatisfied demand-related” exposure measure handles closures of cut links, i.e., links without alternatives. Just as for the importance measures, the need for the “unsatisfied demand-related” exposure measure is avoided in Papers II–V, and the “global” exposure measure is only used in Paper I. It may further be noted that the three measures of expected or average-case exposure assume an equal probability of closure for all links; this is generalized in subsequent papers.

Paper II expands upon the exposure analysis for single link closures in Paper I and introduces the concepts of expected “total” exposure and expected “user” exposure of regions. Just as in (12) and (13) here, “total” exposure refers to the total impact of a certain scenario for all users based in a region, while (mean) “user” exposure refers to the average impact per user based in the region. For the practical calculations of the expected total and user exposure of municipalities and counties it is assumed in the paper that the closure probability p_k of each link is proportional to the length of the link l_k .

Paper V considers regional user exposure to area-covering disruptions. The kind of elements considered is thus not single links but “cells”, i.e., groups of links that all intersect a certain geographical area. The study area is covered with grids of equally sized and shaped cells, and the paper analyses the worst-case user exposure of regions—specifically, counties—across all cells in the grids.

9. Vulnerability and its determinants: Some general results

Each of Papers I–V contains a case study in which the considered vulnerability issues and measures are investigated within a model representation of a real road network, in all instances different parts of the Swedish road network. The case studies provide many specific results that are useful for Swedish transport authorities and other stakeholders, such as the identification of particularly important road segments and particularly exposed regions. However, an important aim of the studies has also been to draw more general conclusions regarding why certain links and areas are more important than others and why certain regions are more exposed than others to various types of scenarios.

Here we summarize some of those findings, which come mainly from the studies presented in Papers II and V. We consider both single link closures and area-

covering disruptions and investigate how their impacts are distributed among users in different regions. The spatial patterns that are found are explained in terms of the properties of the vulnerability metrics and models, and are put in connection with the regional variations in location and travel patterns and network density.

9.1. Data and models

The network and travel demand data (including both car and truck trips) used for the analysis have been extracted from the Swedish national travel demand model system SAMPERS (Beser and Algers, 2001). For more information about this source of data, see Papers I–V. The disruption impacts have been calculated with the model described in detail in Paper III and used in Papers II–V. For the area-covering disruptions, the analysis procedure relies heavily on GIS techniques. GIS software (ArcGIS 9.2) was used to create the cell grids, to identify all cells intersecting the study area and to identify all links and OD nodes intersecting each cell; see further Paper V.

Figure 4 displays some properties of the study area, Sweden, related to location and travel patterns. To the left is shown the population density of each county; as can be seen, the population is mostly concentrated to the southern parts of the country. The left map also shows the locations of the 8764 OD nodes and the level of travel demand generated from each origin. It can be seen that travel demand tends to be concentrated to the east coast in the northern parts of the study area, while it is fairly evenly distributed in the southern parts. To the right is shown the mean trip travel time of each county. Although varying significantly between regions, there are no clear spatial trends to be seen. Paper II discusses the properties of the study area, including variations in network density and traffic load, in more detail. The structure of the road network can be seen in Figure 5 below.

9.2. Link and cell importance

As described in Section 5, we approach vulnerability and the impacts of road network disruptions from two different perspectives. From the first perspective we focus on the element, i.e., the link or cell, that is closed. The importance of an element is given by formula (11) above.

When the element is a single link, it is fairly straightforward to see the determinants of its importance. As noted in Papers II and III, a link is important if it is used by many, i.e., the flow on the link is high, and if the alternatives for the affected users are poor on average. The quality of the alternatives, in turn, depends on the local redundancy in the network around the closed link. As a result, we expect to find important links in densely populated areas, because of large flows on the links, as well as in sparse areas, because of poorly developed networks—consider, for example, the urban I-35W freeway in Minneapolis, USA and the rural

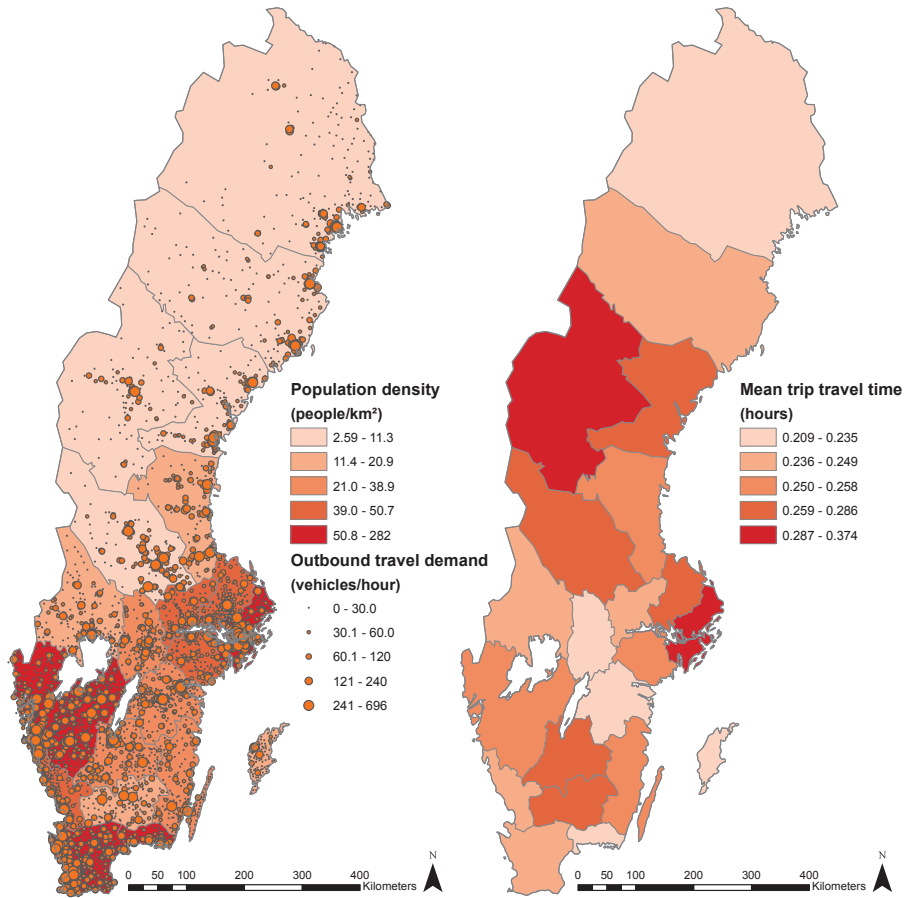


Figure 4: Characteristics of the study area, Sweden. Left: Population density of counties (people/km²), outbound travel demand of origin/destination nodes (vehicles/hour). Right: Mean trip travel time of counties (hours).

E14 highway west of Östersund in Sweden. The longer the closure duration τ , the more important are cut links (i.e., links without alternatives) considered relative to other links.

When the element is a cell, importance refers to the total impact of closing all links intersecting the cell. Such a disruption means that no trips can be made within, into or out of the area covered by the cell; hence, all such travel demand will be unsatisfied. In addition, some trips normally going through the cell may suffer delays or may not be possible to make during the closure. For small cells, representing very local disruptions, few links and OD nodes will be contained in each cell. Hence, cell importance will correspond closely to link importance in this case.

For large cells, on the other hand, the number of internal, inbound and out-

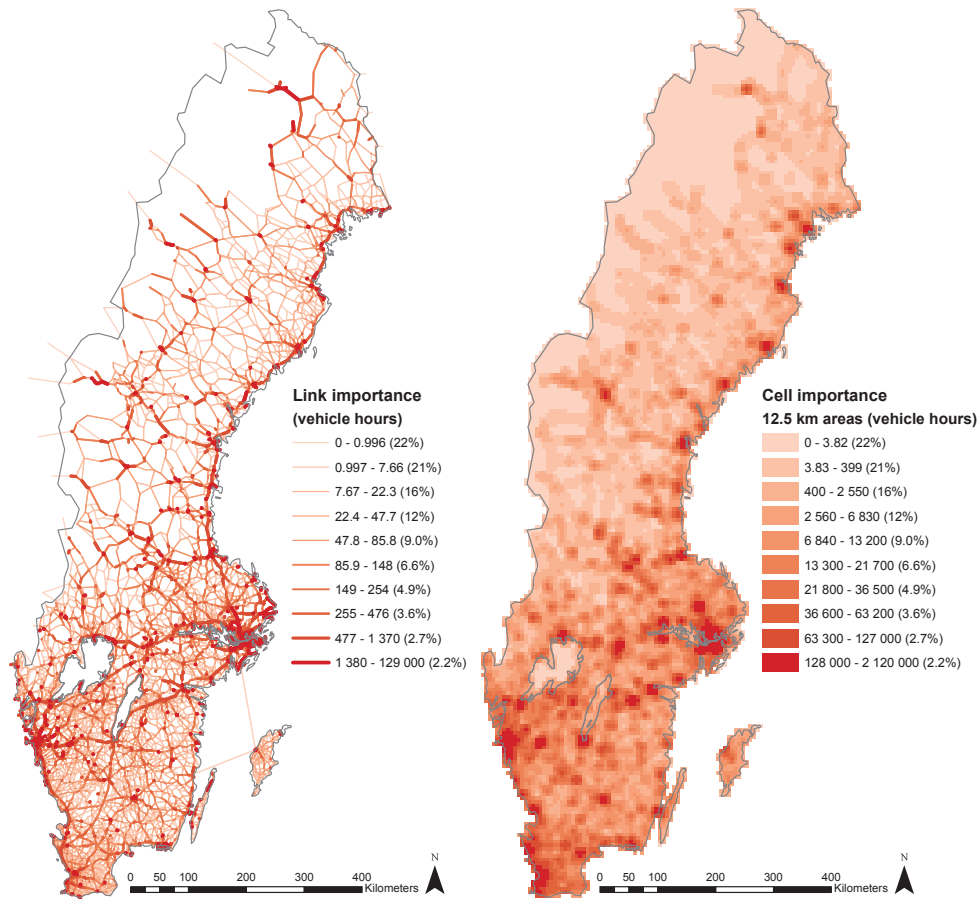


Figure 5: Element importance, 12 hour closure duration. Left: Single links. Right: $12.5 \times 12.5 \text{ km}^2$ cells. The percentages indicate the share of elements in each category.

bound trips will dominate over through trips, and the importance of a cell will mainly be determined by the travel demand generated within the cell itself. In other words, the impacts will be largest where the most people are localized. Therefore, as noted in Paper V, location patterns rather than network structure or travel patterns play the most significant role for the importance of large cells. As for single links, the longer the closure duration, the larger influence unsatisfied demand has relative to through trips that suffer delays.

Figure 5 shows the importance of every link in the Swedish road network model to the left and every $12.5 \times 12.5 \text{ km}^2$ cell in the grids covering the study area to the right, assuming a 12-hour closure in both cases. The left map shows that many important links can be found around the two main urban areas Stockholm and Gothenburg on the east and west coasts, respectively. These links are mainly important because of the large number of travellers using them (since we do not

consider congestion effects in the calculations, these links are likely even more important in reality). There is also a significant number of important links in the sparse northern regions. These are important mainly because of the poor local redundancy around the links; in some cases there are no alternative routes at all. Additional cut links can be found scattered around in all regions of the study area, often appearing only as small dots on the map.

The right map showing cell importance bears some similarity to the left map in that some influence of the network structure can be seen, particularly in the north; this is an effect of the relatively small cells that we consider. However, there is an even clearer influence from the concentration of travel demand as shown to the left in Figure 4. This confirms the general observation that the impacts of area-covering disruptions are most severe in regions with highly concentrated travel demand. Hence, for example, the southernmost part of the country, where both the population and the road network are dense, is typically affected much worse by cell closures than single link closures in terms of overall impact.

9.3. Worst-case regional user exposure

When the elements are single links, the worst-case regional user exposure, formula (14) above, represents the largest possible impact of a single link closure of a particular duration on the users starting within the region, which corresponds to finding the most important link for the region. It can be seen that the worst-case user exposure will be high if a large share of the regional trips normally use a link with particularly poor alternatives. The longer the closure duration, the more likely it is that the most important link for the region is a cut link without any redundancy. In the case of Sweden, Paper II finds that the presence or absence of cut links in a region has little connection with the general density of the regional road network. Furthermore, adding a single new link that provides redundancy to a cut link could drastically improve the worst-case user exposure of a region. This discussion also implies that the metric is quite sensitive to the details of the network model.

As we saw above, the impact of a cell closure is largely determined by the concentration of travel demand within the cell itself. Paper V finds that as a consequence of this, the worst-case user exposure of a region when the elements are cells will be high if a large share of the total regional travel demand is concentrated to the area covered by the disruption, whereas the network density is of little influence. Thus, regions that have a central settlement where a large share of the trips originate and terminate will be particularly exposed to this kind of scenario. At the opposite end are regions with highly dispersed location and travel patterns.

Figure 6 shows the worst-case user exposure of every county in Sweden with respect to single link closures to the left and 12.5 km cell closures to the right. It can be noted that the two maps do not show any great similarity with each other. This is not unexpected since the worst-case exposure to single link closures is highly

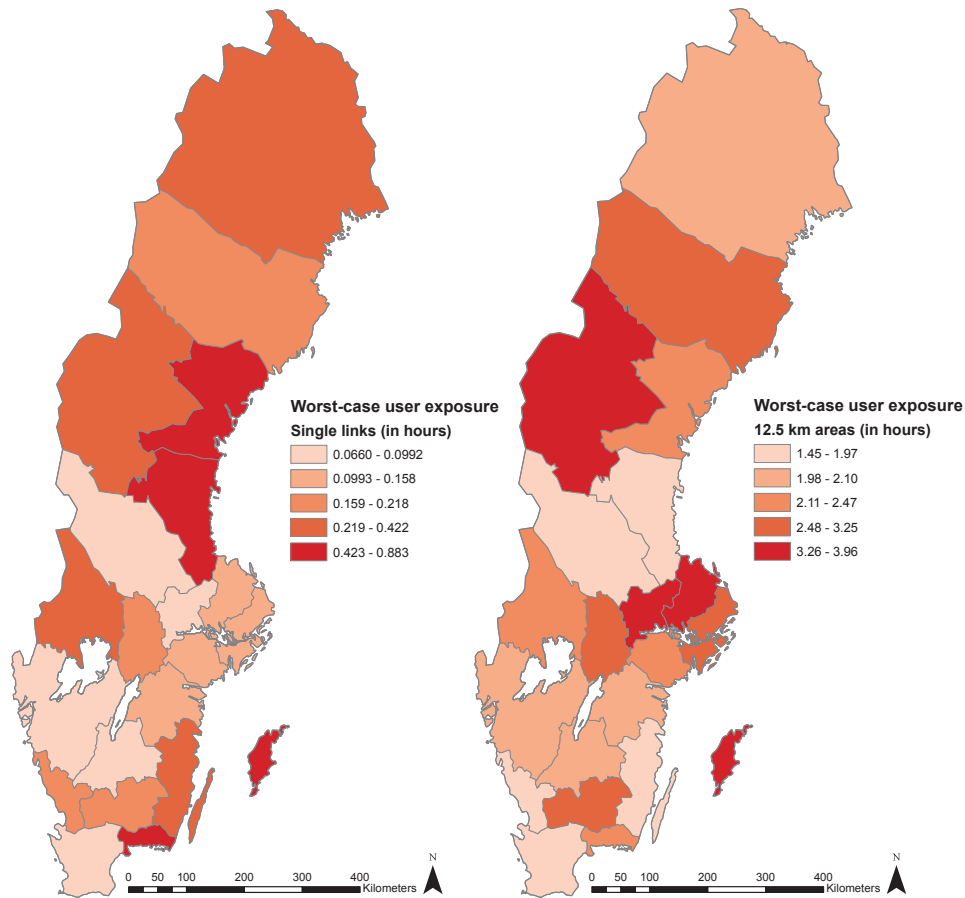


Figure 6: Worst-case user exposure of Swedish counties, 12 hour closure duration. Left: Single link closures. Right: $12.5 \times 12.5 \text{ km}^2$ cell closures.

dependent on the seemingly arbitrary locations of cut links. For cell closures the spatial pattern reflects the extent to which the travel is concentrated to a single central settlement in each county.

9.4. Expected regional user exposure

To calculate expected regional user exposure, formula (15), each disruption scenario must be associated with a normalized probability of occurrence. Here we use the approach sometimes known as Laplace's Principle of Indifference (e.g., Keynes, 1921) which says that all scenarios should be regarded as equally probable if there is no evidence to the contrary. Although there is good reason to believe that disruption probabilities vary geographically we currently lack the empirical basis for a more refined model. Thus, for single link closures we assume that ev-

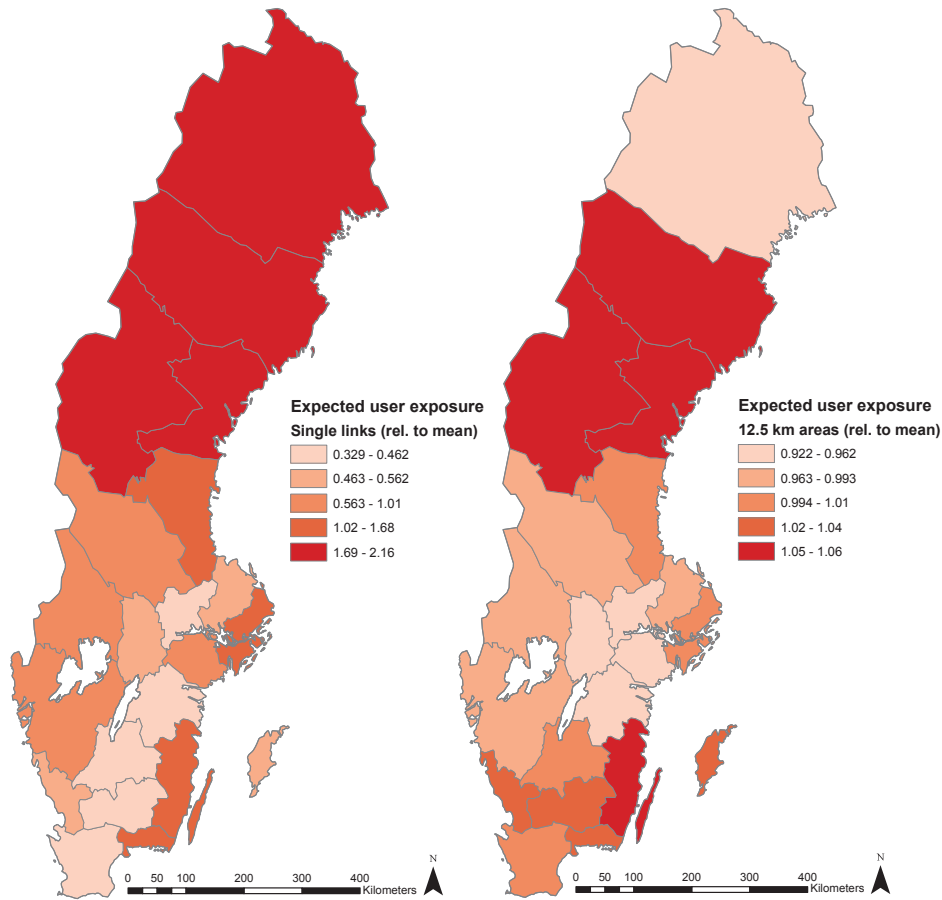


Figure 7: Expected user exposure of Swedish counties, 12 hour closure duration. Left: Single link closures. Right: 12.5 km cell closures.

ery road segment of unit length has the same probability of being closed. This means that the closure probability is proportional to the length of the link, which represents a first approximation of the relative probability that some external event disrupts each link. For area-covering disruptions we assume that each cell has the same probability of being closed. This again represents an external event that is equally likely to occur anywhere in the study area.

As shown in Paper II, the expected user exposure of a region to single link failures is large if the trips are long on average, so that the users have a large chance of using the road segment that is closed, and if the regional density of the network is low, so that the alternative routes are considerably worse on average. For long closure durations, regions where a large share of the trips normally use cut links are particularly exposed. Thus, expected user exposure is influenced by travel patterns as well as the development of the regional road network.

The determinants behind the expected user exposure to area-covering closures are not as easy to characterize as for the other vulnerability metrics we have considered. For example, the concentration or dispersion of the population within the region, although critical for the worst-case scenario, should have only limited effect for the expected exposure. This is because any particular trip cannot be made if either its origin or its destination is located within the disrupted cell, and the mean impact is not dependent on whether a few cells each disrupt a large share of the trips or whether many cells each disrupt a small share of the trips. However, it seems reasonable that the factors that underlie the expected user exposure to single link closures, trip length and network density, should also be influential under cell closures, in particular when the cells are small. Long trips run a larger risk of being affected by area-covering closures, which increases the expected user exposure of the region. Furthermore, poor redundancy in the network means that through trips will have worse or no alternative routes to take when a cell is closed. The longer the closure duration, the larger influence cells with no redundancy around them (“cut cells”) should have.

Figure 7 presents the expected user exposure of the Swedish counties with respect to single link closures to the left and 12.5 km cell closures to the right. As expected from the discussion above, some correlation can be discerned between the two maps, suggesting that similar factors underlie both vulnerability metrics. There are also noticeable differences, however, for example that the northernmost county is highly exposed to single link closures while relatively unexposed to area-covering closures compared to the other counties. This difference may be an effect of the sparse regional road network, which means that area-covering disruptions only have moderately worse impacts than single link closures, whereas the differences are much larger in other areas.

10. On the delay costs of road network disruptions

Estimates of the travellers’ costs associated with delays due to road network disruptions have been performed in connection with several major real-world events, for example the 1994 Northridge earthquake (Wesemann et al., 1996), the 2006 landslide in Småröd, Sweden (MSB, 2009), and the I-35W bridge collapse in Minneapolis 2007 described in Section 3.1 (Xie and Levinson, 2009). In these studies, the approach has been to calculate the delays caused by the disruption using a transport modelling system, typically based on user equilibrium traffic assignment, and then multiply the delays with a standard value of time to obtain a monetary cost.

However, there are several reasons to believe that the cost per hour delay due to a significant unplanned road network disruption is higher than the ordinary value of time. First, it is well known that delay time is considered less enjoyable by travelers than typical travel time (e.g., Wardman, 2001; Bates et al., 2001). Second,

the unexpected nature of unplanned disruptions, the disturbance of normal travel conditions and associated uncertainty during the first few days means that travelers are less able to adjust their schedules adequately beforehand to compensate for the travel time increases. Third, it is likely that a disruption induces travel time increases on more than one trip during the day, such as both the morning and the evening commute. If delay occurs only on the morning trip, a flexible work schedule makes it possible to compensate for late arrival to work by working longer in the evening. If delay affects both commute trips, however, this restricts the possibility to make up for late arrival by working later, which should amount to higher costs.

Paper VI develops a modelling approach to assessing these costs that is closely tied to the formal micro-economic framework in Section 6. The model is *activity-based*, meaning that the activities between which trips are made are explicitly incorporated, and considers a single day in isolation. It is mainly focused on work trips, so that three activities—(1) being at home in the morning, (2) working during the day, and (3) being at home in the evening—and two trips—(1) the morning and (2) the evening commute—are considered. The travel times on the two trips, denoted $T_1(\sigma)$ and $T_2(\sigma)$, are exogenous and depend on the considered scenario σ (compare Section 6); in fact, the travel times are the only ways in which the scenario affects the traveller in the model.

The model is used to analyse the impact of increasing one or both travel times under different assumptions about information and schedule flexibility. The decision variables for the traveller, and the way through which the information aspect enters the model, are the departure times of the two trips, denoted t_{d1} and t_{d2} . Together with the travel times, the departure times determine the arrival times to the subsequent activities, $t_{s2} = t_{d1} + T_1(\sigma)$ (work) and $t_{s3} = t_{d2} + T_2(\sigma)$ (home in the evening).

At each point in time t during the day, *marginal utility* functions express the utility of spending a unit of time in each activity or travelling. The marginal utility of travel for user n is denoted v_n and is assumed to be constant, while the marginal utility for the morning and evening activities are denoted $u_{n1}(t)$ and $u_{n3}(t)$ and are assumed to depend on the time of day. The work activity, finally, is assumed to be partially flexible, so that the marginal utility depends on both the time of day t and the time since arrival $t - t_{s2}$, with a flexibility parameter $\xi_n \in [0, 1]$ controlling the relative influence of each component. The marginal utility function is thus $u_{n2}(t - \xi_n t_{s2})$.

The total utility obtained by individual n in scenario σ is obtained by integrating the marginal utility over the entire day in accordance with the chosen departure times t_{d1} and t_{d2} :

$$\begin{aligned}
U_n(\sigma | t_{d1}, t_{d2}) = & \int_0^{t_{d1}} u_{n1}(t)dt + \int_{t_{d1}+T_1(\sigma)}^{t_{d2}} u_{n2}(t - \zeta_n[t_{d1} + T_1(\sigma)])dt \\
& + \int_{t_{d2}+T_2(\sigma)}^1 u_{n3}(t)dt + v_n[T_1(\sigma) + T_2(\sigma)]. \quad (16)
\end{aligned}$$

Under normal conditions, that is, in a null scenario σ_0 , travellers are assumed to choose departure times optimally so as to maximize the obtained utility $U_n(\sigma_0)$. The impact of a disruption scenario σ is thus captured by the difference in utility $U_n(\sigma | t_{d1}, t_{d2}) - U_n(\sigma_0(\sigma))$. Following the formal framework, our monetary measure of the impact is the compensating variation (CV) required to restore utility to the baseline level $U_n(\sigma_0(\sigma))$. Under certain assumptions about the influence of income on utility, the units of utility can be chosen so that utility differences represent the compensating variation directly, i.e., $\Delta C_n(\sigma | t_{d1}, t_{d2}) = U_n(\sigma | t_{d1}, t_{d2}) - U_n(\sigma_0(\sigma))$ (see Mas-Colell et al., 1995; Tseng and Verhoef, 2008). We use this fact to specify and calibrate functional forms for the marginal costs based on empirical estimation results from Tseng and Verhoef (2008); details about this procedure are found in Paper VI.

The travellers' choices of departure times under the disruption scenario σ depend on the accuracy of the information they possess about the travel times on the given day. We consider three basic types of schedule adjustments: In the first, the user makes no adjustment of the departure times relative to the baseline scenario, representing an individual with no information about the disruption. In the second adjustment type, the user overestimates the delays due to the disruption (by 50%) and departs earlier than necessary. Finally, in the third type, the user has accurate information about the travel conditions and is able to adjust the departure times optimally. For each of the first two adjustment types, a variant is considered in which the user is able to gather accurate information during the day and optimally time the evening commute, giving five different adjustment profiles in total.

Now, for each adjustment type we are interested in calculating travellers' average CV (or simply cost) $\Delta C(\Delta T)$ as a function of the journey delay $\Delta T = T_1(\sigma) + T_2(\sigma) - T_1(\sigma_0) - T_2(\sigma_0)$. Some results are illustrated in Figure 8. Based on the calibrated functions, the figure shows the average cost per hour delay $\Delta C/\Delta T$ for both a completely fixed ($\zeta = 0$) and a completely flexible ($\zeta = 1$) work activity. The cost is calculated for delays ranging from 0 to 5 hours symmetrically distributed on the two trips, for the five schedule adjustment types described above. The value of time (VOT) is calculated for a marginal change in travel time also symmetrical in the two trips, and the baseline travel time is set to 40 minutes on both trips.

As can be seen, the delay costs increase rapidly for all adjustment types, although at diminishing rates, and are considerably higher than the marginal value of time. By construction the delay cost is lowest for the optimal adjustment profile,

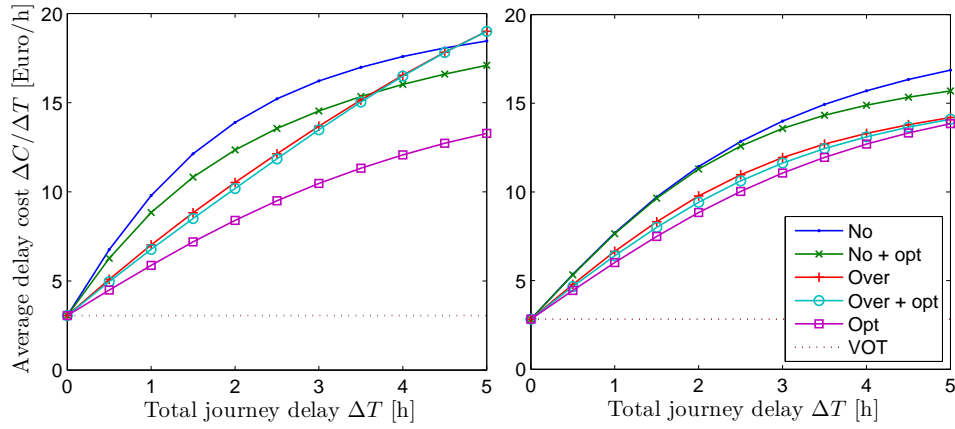


Figure 8: Average delay cost per hour delay, $\Delta C/\Delta T$, with delay symmetrical on the two trips. Baseline travel time is 2×40 minutes. Left: Fixed work schedule ($\xi = 0$). Right: Flexible work schedule ($\xi = 1$).

since optimizing the schedule against the delays is equivalent to minimizing the travel costs. For the two profiles involving no adjustment of the morning departure time, the costs are slightly higher with a fixed work schedule, which reflects that time lost from work is more costly in the morning than in the evening. The cost for the no + optimal adjustment type—i.e., travellers who retain their pre-disruption departure time on trip 1 but optimally reschedule trip 2—is only slightly lower than the pure no adjustment profile. In this case there is thus little to be gained from rescheduling the evening trip since it will be optimal to take most of the journey delay in the form of late arrival at home.

The costs for the two over-adjustment profiles are restricted to even smaller intervals, which shows that the early departure and arrival in the morning are the main contributors to the delay costs. With a fixed schedule, over-adjustment leads to lower costs than no adjustment for moderate delays, but this advantage diminishes and is even reversed for long delays. The high costs for long delays are more due to the inconvenience of arriving early to work than to that of departing early from home. With a flexible schedule the costs of over-adjustment are considerably lower, since there is no cost associated with arriving early to work; on the contrary, early arrival gives more time to spend at work or at home in the evening.

11. Conclusion and challenges for the future

This thesis develops the methodology for quantitative vulnerability analysis of infrastructure systems in general and the road transport system in particular. A formal framework for infrastructure vulnerability analysis is formulated and put into op-

erational form for the road network. Studies of different aspects of road network vulnerability are carried out, with a particular focus on the dichotomy of system efficiency and user equity. We introduce the concepts of link importance as the overall impact of closing a particular link, and regional exposure as the impact for individuals in a particular region of, e.g., a worst-case or an average-case scenario (Paper I). By construction, a link is important if the normal flow across it is high and/or the alternatives to this link are considerably worse, while a traveller is exposed if a link closure along her normal route is likely and/or the best alternative is considerably worse. We show, for example, that these relationships can be generalized to municipalities and counties, so that geographical variations in vulnerability can be explained by variations in network density and travel patterns (Paper II).

We also study the vulnerability of the road network under area-covering disruptions, representing for example flooding, heavy snowfall or forest fires. In contrast to single link failures, the impacts of this kind of events are largely determined by the population concentration, more precisely the travel demand within, in and out of the disrupted area itself, while the density of the road network is of small influence (Paper V).

Finally, the thesis approaches the issue of how to value the delays that are incurred by network disruptions and, using an activity-based modelling approach, we illustrate that these delay costs may be considerably higher than the ordinary value of time, in particular during the first few days after the event when travel conditions are uncertain (Paper VI).

11.1. Vulnerability management

The research of this thesis is mainly concerned with analysing the vulnerability of a given road transport system and not much with how to *manage* the vulnerability with emergency preparedness, infrastructural reinforcements and expansions, operations and maintenance procedures etc. This tendency appears to hold for the quantitative vulnerability literature in general, which suggests that there is a need for more *normative* approaches in model-based vulnerability analysis. That is, given the society's current state of vulnerability to disruptions in the road transport system, what actions should be taken?

In the planning stage, a vulnerability analysis can for example guide the alignment and standard of a new road, or support the building of a new road that among other benefits provides some redundancy to the existing roads. *Robust network design*, i.e., how to design a road network from scratch or in the long run to be able to handle severe disruptions, has been studied theoretically by for example Zhang and Levinson (2004) and Immers and Bleukx (2008) and applied to the Dutch highway system by Snelder et al. (2010). Goodwin (1992) also suggests that transport systems should be planned so as to have some additional redundancy and spare capacity that would not be motivated when only considering transport efficiency.

During the operations stage, different actions can be taken to reduce the vulnerability depending on the type of identified hazard or threat. As examples of how to reduce the likelihood of incidents, traffic accidents may be avoided by straightening or widening the road or reducing the speed limit, technical failures may be avoided with more thorough inspection and maintenance, and natural hazards may be avoided by upgrading the road structure, such as switching to larger drain pipes to handle floods. To reduce the consequences of a disruption once it has occurred the main issue is to restore the performance of the network as rapidly as possible, for example by increasing the resources for stand-by maintenance preparedness, while information provision is important for limiting the effects of the degradation while it lasts.

Some general observations regarding the efficiency of different kinds of actions may be made from the studies presented above and in Papers II and V. Given certain spatial extents, durations and relative probabilities, these studies found significant influences on regional variations in vulnerability from travel patterns, location patterns and the development of the road network. In practice, road investments of typical size will likely have little influence on these fundamental properties of the transport system and the population distribution within a reasonable planning horizon. Therefore we believe that resource allocation for reducing vulnerability is more an issue of prevention and preparedness for quick mitigation and restoration than redundancy-providing but expensive infrastructure investments. An exception may be identified worst-case scenarios and hot spots, for which targeted actions such as road investments improving local redundancy may have considerable positive effects. Of course, the benefits of such investments must be put in relation to their costs.

Given a certain assigned budget for investments aimed at reducing vulnerability, the problem arises of how to allocate those resources. As in cost-benefit analysis (CBA) in general, we should ideally assess the benefits and costs of the various possible investments, and the actions giving the highest total benefits-to-costs ratio within the available budget should then be taken. Since all investments considered here concern vulnerability, i.e., the frequencies and impacts of transport system disruptions, this kind of CBA can be performed reasonably accurately even if not all relevant components of the costs are included, as long as these omitted components make up fairly similar shares across the different projects (cf. Dalziell and Nicholson, 2001). For example, the model used to calculate the costs of delays may be overly conservative and underestimate the benefits of reducing delays, but this may not affect the selection of projects much as long as the relative underestimations are similar across disruption scenarios. Furthermore, it is only necessary to assess *relative* frequencies of different disruption scenarios, which significantly increases the tractability of the analysis.

Practical methods for performing this kind of cost-benefit assessments have already been implemented in for example Sweden, where the focus is in partic-

ular on reducing the probabilities that disrupting events such as floodings occur (Löfling, 2005). We believe that refining the methodology and gaining general insights regarding different types of actions (prevention, restoration, etc.) is a venue where immediate research contributions can be made. For example, there is much work to be done in identifying, modeling and assessing the full disruption costs for individuals, businesses and authorities.

A considerably more complicated problem is how to set the budget for vulnerability management. That is, how much—if any—resources should be spent on vulnerability-reducing actions rather than on projects and investments fulfilling other goals? A similar problem arises when projects have impacts on vulnerability as well as on efficiency, safety, emissions etc., and one needs to determine how much weight to put on the vulnerability aspect when ranking the projects. Assuming that the societal cost of vulnerability can be calculated as the total cost of all disruptions occurring, this requires for example that the frequencies with which different scenarios will occur must be assessed in absolute rather than relative numbers. Since one of the inherent difficulties surrounding risk, uncertainty and vulnerability is predicting the events that will occur (be it natural hazards, antagonistic attacks, technical failures, accidents, etc.), this is a daunting if at all possible task, although ideas from the extreme value literature and other fields may possibly be adopted (see for example Holmgren and Molin, 2006).

It has been shown empirically that there is an *option value* associated with public transport services, i.e., people are sometimes willing to pay more (through, e.g., increased taxes) for the provision of a service that can act as backup to their normal means of travel than their expected benefit from the service (Laird et al., 2009). It seems reasonable that there should be option values associated with other components of the transport systems as well, such as links in the road network. An interesting research question is thus if the option value, which reflects users' internalized probability perceptions and risk aversion, may be a mechanism through which vulnerability issues can enter the CBA framework.

11.2. Vulnerability of other transport systems

The road transport system is part of the overall transport infrastructure that also includes for example the railway, waterway and airway transport systems. At best, different systems can complement each other so that a single trip or freight delivery can be made through multiple systems, as when taking a train to the airport, flying to another city and taking a taxi to the final destination. Such serial connections can have positive effects on transport efficiency, accessibility and emissions. There is also a potential for parallel connections, so that one system can act as a backup alternative when another system is disrupted or overloaded. Thus, for example, it is sometimes possible to replace trains with buses during disruptions of the railway.

The possibilities and difficulties of managing vulnerability by redundancy in

transport systems is an area with high potential for interesting research. Already Goldberg (1975) warns against the tendency in planning overall to sacrifice long-run robustness and resilience for short-run and narrow-sighted efficiency gains. One issue concerns the aims and incentives of the system operators. Many transport services are run with the goal of raising profit to the owners, in particular through ticket sales. Having several parallel, substitutable transport systems means competition for customers which may reduce the profits. The unprofitable transport services tend to disappear from the market, increasing the efficiency but lowering the redundancy of the overall transport system. An interesting question is thus how to create an incentive structure for operators that provides both efficiency and redundancy for users.

The vulnerability of other transport systems, in isolation and as parts of the overall transport infrastructure, is not as well explored as for the road network, and there is much need for research in these areas. From a glance, however, it appears that the road network is one of the least vulnerable transport systems. There are several reasons for this: For example, the road infrastructure is typically planned and operated as a societal service financed by local, regional and national taxes rather than as a profit-seeking enterprise, which means that there is no competition that restricts the existence of parallel links and routes in the network. Also, the travel demand served is much more dispersed than for the other transport systems, where it is concentrated to stations, ports and airports. This means that efficient and accessible transport requires much more links between nearby settlements than the other networks do, which, mostly as a side-effect, provides greater redundancy in the system. Further, the flexibility and the autonomous control of the users is higher than in other systems, which means that knock-on impacts may be smaller and that individuals have greater opportunities to adapt to disruptions in ways that are suitable for themselves.

The increasing awareness that the road transport system with its fossil-fueled vehicles is not sustainable has in many countries instigated policies aimed at transferring car and truck trips to other modes of transport, such as buses and trains. Given the hypothesis that the alternative modes are more vulnerable, an interesting research topic is to investigate the impacts of this transition on vulnerability. Furthermore, if users perceive that the alternatives are more vulnerable than the road network, it may even hamper their willingness to switch from car and truck transport to other modes. Concerns of this nature were for example raised after the severe breakdown of train services in Sweden during the winter 2010 (Spängs, 2010).

References

- Aven, T. (2007) A unified framework for risk and vulnerability analysis covering both safety and security. *Reliability Engineering & System Safety* 92, 745–754.
- Ball, M. O., Golden, B. L. and Vohra, R. V. (1989) Finding the most vital arcs in a network. *Operations Research Letters* 8, 73–76.
- Bates, J., Polak, J., Jones, P. and Cook, A. (2001) The valuation of reliability for personal travel. *Transportation Research Part E* 37, 191–229.
- Bell, M. G. H. and Iida, Y. (1997) *Transportation Network Analysis*. Chichester, West Sussex: Wiley.
- Bell, M. G. H., Kanturska, U., Schmöcker, J.-D. and Fonzone, A. (2008) Attacker-defender models and road network vulnerability. *Philosophical Transactions of the Royal Society A* 366, 1893–1906.
- Berdica, K. (2000) Analysing Vulnerability in the Road Transportation System – Putting Theory into Practice Using Sweden as an Example. Licentiate thesis, Dept. of Infrastructure, Royal Institute of Technology, Sweden.
- Berdica, K. (2002) An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy* 9, 117–127.
- Berdica, K., Andjic, Z. and Nicholson, A. J. (2003) Simulating road traffic interruptions – Does it matter what model we use? In Bell, M. G. H. and Iida, Y. (eds), *The Network Reliability of Transport*. Pergamon-Elsevier, Oxford, 353–368.
- Berdica, K. and Mattsson, L.-G. (2007) Vulnerability: A model-based case study of the road network in Stockholm. In Murray, A. T. and Grubestic, T. H. (eds), *Critical Infrastructure: Reliability and Vulnerability*, Advances in Spatial Science. Springer, 81–106.
- Beser, M. and Algers, S. (2001) SAMPERS – The new Swedish national travel demand forecasting tool. In Lundqvist, L. and Mattsson, L.-G. (eds), *National Transport Models: Recent Developments and Prospects*, Advances in Spatial Science. Springer, 101–118.
- Cairns, S., Atkins, S. and Goodwin, P. (2002) Disappearing traffic? The story so far. *Proceedings of the Institution of Civil Engineers. Municipal Engineer* 151, 13–22.
- Chen, A., Yang, C., Kongsomsaksakul, S. and Lee, M. (2007) Network-based accessibility measures for vulnerability analysis of degradable transportation networks. *Networks and Spatial Economics* 7, 241–256.

- Chen, A., Yang, H., Lo, H. K. and Tang, W. H. (2002) Capacity reliability of a road network: an assessment methodology and numerical results. *Transportation Research Part B* 36, 225–252.
- Cho, S., Gordon, P., Moore II, J. E., Richardson, H. W., Shinozuka, M. and Chang, S. (2001) Integrating transportation network and regional economic models to estimate the costs of a large urban earthquake. *Journal of Regional Science* 41, 39–65.
- Clark, S. D. and Watling, D. P. (2005) Modelling network travel time reliability under stochastic demand. *Transportation Research Part B* 39, 119–140.
- Clegg, R. (2007) Empirical studies of road traffic response to capacity reductions. In *Transportation and Traffic Theory 2007: Papers selected for presentation at ISTTT17*. Elsevier Science, 155–178.
- Dalziell, E. P. and Nicholson, A. J. (2001) Risk and impact of natural hazards on a road network. *ASCE Journal of Transportation Engineering* 127, 159–166.
- Department for Transport (2004) The changing climate: Its impacts on the Department for Transport. UK Department for Transport, April 2004.
- D’Este, G. M. and Taylor, M. A. P. (2003) Network vulnerability: An approach to reliability analysis at the level of national strategic transport networks. In Bell, M. G. H. and Iida, Y. (eds), *The Network Reliability of Transport*. Pergamon-Elsevier, Oxford, 23–44.
- Einarsson, S. and Rausand, M. (1998) An approach to vulnerability analysis of complex industrial systems. *Risk Analysis* 18, 535–546.
- Erath, A., Birdsall, J., Axhausen, K. W. and Hajdin, R. (2009) Vulnerability assessment methodology for Swiss road network. *Transportation Research Record* 2137, 118–126.
- Ezell, B. C. (2007) Infrastructure vulnerability assessment model (I-VAM). *Risk Analysis* 27, 571–583.
- Fosgerau, M. and Karlström, A. (2010) The value of reliability. *Transportation Research Part B* 44, 38–49.
- Garrison, W. L. (1960) Connectivity of the Interstate Highway System. *Papers in Regional Science* 6, 121–137.
- Giuliano, G. and Golob, J. (1998) Impacts of the Northridge earthquake on transit and highway use. *Journal of Transportation and Statistics* 1, 1–20.
- Goldberg, M. A. (1975) On the inefficiency of being efficient. *Environment and Planning A* 7, 921–939.

- Goodwin, P. B. (1992) A quality margin in transport. *Traffic Engineering and Control* 33, 661–665.
- Haimes, Y. Y. (2006) On the definition of vulnerabilities in measuring risks to infrastructures. *Risk Analysis* 26, 293–296.
- Ham, H., Kim, T. J. and Boyce, D. (2005) Assessment of economic impacts from unexpected events with an interregional commodity flow and multimodal transportation network model. *Transportation Research Part A* 39, 849–860.
- He, X., Jabari, S. and Liu, H. X. (2009) Modeling day-to-day traffic equilibration after network disruption. Transportation Research Board Annual Meeting 2009 Paper #09-3318.
- Holmgren, Å. J. and Molin, S. (2006) Using disturbance data to assess vulnerability of electric power delivery systems. *Journal of Infrastructure Systems* 12, 243–251.
- Horwath, J. (2007) Federal, state politicians hasten to help. *The Minnesota Daily News* report August 8 2007.
- Høyland, A. and Rausand, M. (1994) *System Reliability Theory: Models and Statistical Methods*. New York, NY: John Wiley & Sons.
- Hunt, J., Brownlee, A. and Stefan, K. (2002) Responses to Centre Street bridge closure: Where the “disappearing” travelers went. *Transportation Research Record* 1807, 51–58.
- Husdal, J. (2004) Reliability and vulnerability versus costs and benefits. Presented at the European Transport Conference (ETC), Strasbourg, France, October 4–6 2004.
- Iida, Y. and Bell, M. G. H. (eds) (2003) *The Network Reliability of Transport*. Pergamon-Elsevier, Oxford.
- Immers, B. and Bleukx, A. (2008) On the robustness of transportation network structures. In Giaoutzi, M. and Nijkamp, P. (eds), *Network Strategies in Europe: Developing the Future for Transport and ICT*. Ashgate Publishing, Aldershot, England, 37–50.
- Jämtlands läns landsting (2006) Raset vid Ånn: Sjukvården fungerar som vanligt igen. Press release 02/08/2006, in Swedish.
- Johansson, J. (2010) Risk and Vulnerability Analysis of Interdependent Technical Infrastructures. Ph.D. thesis, Dept. of Measurement Technology and Industrial Electrical Engineering, Lund University, Sweden.

- Kaplan, S. and Garrick, B. J. (1981) On the quantitative definition of risk. *Risk Analysis* 1, 11–27.
- KBM (2005) Hot- och riskrapport 2005. KBM:s temaserie 2005:11. Krisberedskapsmyndigheten, Sverige. In Swedish.
- Keynes, J. M. (1921) *A Treatise on Probability*. Macmillan & Co., London.
- Kim, T. J., Ham, H. and Boyce, D. E. (2002) Economic impacts of transportation network changes: Implementation of a combined transportation network and input-output model. *Papers in Regional Science* 81, 223–246.
- Klimat- och sårbarhetsutredningen (2007) Sverige inför klimatförändringarna – hot och möjligheter. Miljödepartementet, SOU 2007:60, in Swedish.
- Knoop, V., Zuylen, H. van and Hoogendoorn, S. (2008) The influence of spill-back modelling when assessing consequences of blockings in a road network. *European Journal of Transportation and Infrastructure Research* 8, 287–300.
- Laird, J., Geurs, K. and Nash, C. (2009) Option and non-use values and rail project appraisal. *Transport Policy* 16, 173–182.
- Latora, V. and Marchiori, M. (2007) A measure of centrality based on network efficiency. *New Journal of Physics* 9, 188.
- Little, R. G. (2002) Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures. *Journal of Urban Technology* 9, 109–123.
- Länstidningen Östersund (2006a) E14 öppen för trafik igen. *Länstidningen Östersund* News report 08/01/2006, in Swedish.
- Länstidningen Östersund (2006b) Marken rämnade under rälsen. *Länstidningen Östersund* News report 07/31/2006, in Swedish.
- Länstidningen Östersund (2006c) Slutnotan för raset på E14 blir minst 18 miljoner. *Länstidningen Östersund* News report 09/06/2006, in Swedish.
- Länstidningen Östersund (2006d) Tågstopp och bandvagnar efter vägras. *Länstidningen Östersund* News report 07/31/2006, in Swedish.
- Länstrafiken i Jämtlands Län (2007) Årsredovisning för Länstrafiken i Jämtlands län AB räkenskapsåret 2006-01-01—2006-12-31. Annual report, in Swedish.
- Löfling, P. (2005) Handledning: Riskanalys vald vägsträcka. Vägverket Publikation 2005:54, ISSN 1401–9612. In Swedish.
- Lohn, M. (2007) Rich contract awarded for I-35W bridge replacement. Minnesota Public Radio. News report September 19, 2007.

- Lohn, M. (2008) Minnesota inks deal with bridge victims. CBS News (The Associated Press). News report May 2, 2008.
- Mas-Colell, A., Whinston, M. D. and Green, J. R. (1995) *Microeconomic Theory*. Oxford University Press, New York.
- Matisziw, T. C. and Murray, A. T. (2009) Modeling s - t path availability to support disaster vulnerability assessment of network infrastructure. *Computers & Operations Research* 36, 16–26.
- Moteff, J. and Parfomak, P. (2004) Critical infrastructure and key assets: Definition and identification. CRS Report for Congress RL32631. Congressional Research Service, The Library of Congress, USA.
- MSB (2009) Analys av samhällsekonomisk kostnad: Skredet vid E6 i Småröd, 2006. Swedish Civil Contingencies Agency, Report MSB 0069-09, in Swedish.
- Murray, A. T., Matisziw, T. C. and Grubestic, T. H. (2008) A methodological overview of network vulnerability analysis. *Growth and Change* 39, 573–592.
- Murray-Tuite, P. M. and Mahmassani, H. S. (2004) Methodology for the determination of vulnerable links in a transportation network. *Transportation Research Record* 1882, 88–96.
- Nicholson, A. (2003) Transport network reliability measurement and analysis. *Transportes XI*, 49–62.
- Nicholson, A. J. and Du, Z. P. (1994) Improving network reliability: a framework. In *Proceedings of 17th Australian Road Research Board Conference*, 3, 1–17.
- Noland, R. B. and Polak, J. W. (2002) Travel time variability: A review of theoretical and empirical issues. *Transport Reviews* 22, 39–54.
- Noland, R. B. and Small, K. A. (1995) Travel-time uncertainty, departure time choice, and the cost of morning commutes. *Transportation Research Record* 1493, 150–158.
- NTSB (2008) Collapse of I-35W highway bridge, Minneapolis, Minnesota, August 1, 2007. National Transportation Safety Board. Highway Accident Report NTSB/HAR-08/03. Washington, DC.
- Qiang, Q. and Nagurney, A. (2008) A unified network performance measure with importance identification and the ranking of network components. *Optimization Letters* 2, 127–142.
- Ratliff, H. D., Sicilia, G. T. and Lubore, S. H. (1975) Finding the n most vital links in flow networks. *Management Science* 21, 531–539.

- Rinaldi, S., Peerenboom, J. and Kelly, T. (2001) Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine* 21, 11–25.
- Scott, D. M., Novak, D. C., Aultman-Hall, L. and Guo, F. (2006) Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks. *Journal of Transport Geography* 14, 215–227.
- Snelder, M., Immers, B. and Ruijgrok, K. (2010) Design principles for improving the robustness of networks. Presented at the 4th International Symposium on Transport Network Reliability (INSTR), July 22–23 2010, Minneapolis, USA.
- Sohn, J. (2006) Evaluating the significance of highway network links under the flood damage: An accessibility approach. *Transportation Research Part A* 40, 491–506.
- Spängs, T. (2010) Green Cargo räknar med mångmiljonförluster. *Dagens Nyheter*, news report March 5 2010. In Swedish.
- State of Minnesota (2008) Economic impacts of the I-35W bridge collapse. Minnesota Department of Employment and Economic Development, Minnesota Department of Transport. PM.
- Suarez, P., Anderson, W., Mahal, V. and Lakshmanan, T. R. (2005) Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the boston metro area. *Transportation Research Part D* 10, 231–244.
- Sullivan, J., Novak, D., Aultman-Hall, L. and Scott, D. (2010) Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A* 44, 323–336.
- Tatano, H. and Tsuchiya, S. (2008) A framework for economic loss estimation due to seismic transportation network disruption: A spatial computable general equilibrium approach. *Natural Hazards* 44, 253–265.
- Taylor, M. A. P. (2008) Critical transport infrastructure in urban areas: Impacts of traffic incidents assessed using accessibility-based network vulnerability analysis. *Growth and Change* 39, 593–616.
- Taylor, M. A. P. and D’Este, G. M. (2004) Critical infrastructure and transport network vulnerability: Developing a method for diagnosis and assessment. In Nicholson, A. and Dantas, A. (eds), *Proceedings of the Second International Symposium on Transportation Network Reliability (INSTR)*. Christchurch, New Zealand, 96–102.

- Taylor, M. A. P., Sekhar, S. V. C. and D'Este, G. M. (2006) Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics* 6, 267–291.
- Transportation Research Board (2008) Potential impacts of climate change on US transportation. Transportation Research Board Special Report 290.
- Tseng, Y.-Y. and Verhoef, E. (2008) Value of time by time of day: A stated-preference study. *Transportation Research Part B* 42, 607–618.
- Vägverket (2006a) E14 öppnas för all trafik redan i dag fredag klockan 13.00. Press release 08/11/2006, in Swedish.
- Vägverket (2006b) E14 öppnas för provisorisk personbilstrafik idag kl 19.00. Press release 08/01/2006, in Swedish.
- Vägverket Produktion (2006) Rekordsnabb återuppbyggnad av E14. Press release 08/14/2006, in Swedish.
- Wakabayashi, H. and Iida, Y. (1992) Upper and lower bounds of terminal reliability in road networks: an efficient method with Boolean algebra. *Journal of Natural Disaster Science* 14, 29–44.
- Wardman, M. (2001) A review of British evidence on time and service quality valuations. *Transportation Research Part E* 37, 107–128.
- Watling, D. (2008) Modelling and evaluation of reliability impacts in road networks: Concepts and methods for traffic assignment models. Presented at the European Transport Conference (ETC) 2008.
- Wesemann, L., Hamilton, T., Tabaie, S. and Bare, G. (1996) Cost-of-delay studies for freeway closures caused by Northridge earthquake. *Transportation Research Record* 1559, 67–75.
- Willis, H. H. (2007) Guiding resource allocations based on terrorism risk. *Risk Analysis* 27, 597–606.
- Xie, F. and Levinson, D. (2009) Evaluating the effects of I-35W bridge collapse on road-users in the Twin Cities metropolitan region. *Transport Planning and Technology*, forthcoming.
- Yang, H., Lo, H. K. and Tang, W. H. (2000) Travel time versus capacity reliability of a road network. In Bell, M. G. H. and Cassir, C. (eds), *Reliability of Transport Networks*, Research Studies. Baldock, Herts, 119–138.

Zhang, L. and Levinson, D. (2004) Investing for robustness and reliability in transportation networks. In Nicholson, A. and Dantas, A. (eds), *Proceedings of the Second International Symposium on Transportation Network Reliability (INSTR)*. Christchurch, New Zealand, 160–167.

Zhu, S., Levinson, D. and Liu, H. (2010a) Measuring winners and losers from the new I-35W Mississippi river bridge. Presented at 89th Transportation Research Board Conference, January 2010, Washington D.C.

Zhu, S., Levinson, D., Liu, H. and Harder, K. (2010b) The traffic and behavioral effects of the I-35W Mississippi river bridge collapse. *Transportation Research Part A*, accepted for publication.