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Approaches to Road Network Vulnerability Analysis

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Abstract

Incidents in the road transport system can have large negative consequences for the society and the business community. The basic aim of vulnerability analysis is to identify scenarios that i) would lead to severe consequences, and ii) have some likelihood of being realized in the future.

The Thesis proposes two main approaches to vulnerability analysis. The first significant component of the analysis is to identify *important* links in the road network, i.e., links where a disruption would lead to severe consequences. The second component is to identify *exposed* users, i.e., users for which the consequences of a disruption would be particularly severe.

Paper I introduces the concepts of importance and exposure and how they can be operationalized in terms of increased travel time when road links are closed. The measures are applied to the road network of northern Sweden. Among other things, we find that the most important road links from a socio-economic efficiency perspective are sections of the main roads in the region going through the main population centres. The most exposed users, on the other hand, live in the sparsely populated municipalities in the northwest along the Norwegian border.

Paper II studies the geographic patterns of exposure and importance in Sweden and identifies properties of the geography, road network and travel patterns that to a large extent explain the observed spatial differences. We find that the municipalities around Stockholm have the most important road networks, and that people in the southern parts of Sweden are considerably less exposed than in the northern parts. We also find that the sparsity of the road network, the travel times of the users and the traffic load on the links provide good explanatory variables for the regional variations in exposure and importance.

Paper III proposes a link importance measure that incorporates both efficiency considerations, i.e. the total increase in travel time, and equity considerations, i.e. the unevenness of the distribution among users. We show analytically that there is a strong inverse relationship between the two components. In a case study of the Swedish road network we find that when only efficiency is considered, links in many of the main roads are among the most important. With more weight put on equity, importance is gradually shifted to smaller local roads with poor or no alternative routes.

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List of Papers

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III. Jenelius, E. (2007b) Considering the user inequity of road network vulnerability. Submitted.

Contents

1 Road network vulnerability: an illustration

At around 6:45 pm on Sunday, 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.

The road is an important connection between Sweden and Norway, 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.

On Friday, 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. I have not seen any estimation of the full socio-economic cost of the event. The information presented here has been collected from Länstidningen Östersund (2006a,b,c,d), Vägverket (2006a,b), Vägverket Produktion (2006) and Jämtlands läns landsting (2006).

2 Vulnerability analysis: motivation, aim and value

The disruption of the E14 illustrates the basic premise behind road network vulnerability: Sometimes incidents in the road transport system occur that have large negative consequences for the society and the business community. Some incidents, for instance car accidents, may cause casualties directly. There may also be large costs associated with restoring the transport system to a fully operational state. We, however, will be more concerned with the impacts that are due to the reduced performance of the road transport system, e.g. a road being cut off.

We may roughly divide the range of possible consequences of reduced system performance into two categories based on their immediacy. First, there are disturbances in services that if not available at all times will threaten life and health. One such service is the ability for people to receive emergency medical care. In a worst-case scenario, an incident may cut off all possibilites to reach a hospital or for an ambulance to reach the person in need; in other cases, the best alternative route may be unreasonably 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 perspective, 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 may include delayed deliveries and supplies (with possible ripple effects), increased freight costs, delayed or cancelled business meetings, etc. All these impacts are associated with socio-economic costs.

The overall objective of the Swedish transport policy is to ensure a socio-economically efficient and long-term sustainable transport provision for the people and the business community in the whole country. Similar formulations are likely among the primary objectives of most national transport authorities. In view of this, there should be a great interest in assessing the socio-economic impacts of incidents in the road transport system.

Many types of incidents can potentially cause severe disturbances in the road transport system. To begin with, some are caused by the traffic itself, in the form of car accidents or exceptional congestion due to sport events or the like. Some incidents are caused by external accidents such as industrial leakages or ships ramming bridges[1]; others are caused by technical failures of the road structure, bridges, etc., due to wear and tear or faulty construction[2]. Still others are caused by adverse meteorological, hydrological or geological conditions, e.g. flash floods, snow storms, landslides and eartquakes, that either disrupt the road network or obstruct the traffic[3]. Furthermore, we cannot ignore the reality of intentional attacks on the transport system, e.g. as a means to inflict disorder and panic to the society or to delay the police after a robbery[4]. 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.

Recently, a commission investigating the consequences for Sweden of the anticipated climate changes presented its report (Klimat- och sårbarhetsutredningen, 2007). Among its conclusions are that the risk for floods, landslides and erosion will increase in many areas, affecting houses, railways and roads. For the road network, the costs associated with these damages between the years 2010 and 2100

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[1] E.g., the ramming of Essingeleden in Stockholm, Sweden, October 14 2005.

[2] E.g., the collapse of the I-35 W bridge in Minnesota, USA, August 1 2007.

[3] E.g., the landslide at the E6 European highway in Munkedal, Sweden, December 20 2006.

[4] E.g., the robbery of a valuables transport van in Hallunda, Sweden, August 29 2005.

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.

The basic aim of vulnerability analysis, as defined in this Thesis, is to identify scenarios that i) would lead to severe consequences for the society and the business community, and ii) can be considered to have some likelihood of being realized in the future. Following Holmgren (2007), the vulnerability analysis can be framed with the following four questions:

i. What can go wrong?

ii. What are the consequences?

iii. How likely is it to happen?

iv. How is a normal state restored?

The basic goal of vulnerability analysis can be disaggregated and refined in many subgoals. An important part of the analysis is to identify critical points or regions in the road network where some kind of incident would lead to particularly severe consequences, and where the potential for such incidents in the future cannot be considered negligible. Another important task is to identify users or regions for which the consequences of an incident would potentially be particularly severe.

Road network vulnerability analysis gives the road authorities the ability to counteract discovered vulnerabilities before they are realized, which is valuable during both the planning stage and the operations stage. In the planning stage, the analysis can e.g. prevent locating a new road nearby potential hazards, or support the building of a new road that—among other benefits—provides some redundancy to the existing roads. 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 avoided by upgrading the road structure, such as switching to larger drain pipes to handle floods. To reduce the consequences of an incident, the main issue is to restore the performance of the network as rapidly as possible, e.g. by increasing the resources for stand-by maintenance preparedness.

3 Vulnerability and related concept

The word vulnerability is generally used in every-day language to express a "sensitivity to attack or injury". The term is used in a wide range of contexts, e.g. in psychology, sociology, biology, computer science and warfare, and there is no precise definition of vulnerability that is applicable in all fields (see further McEntire, 2005). On the other hand, the road transport system has much in common with the other technical infrastructures such as the electric power system, the water and sewage supply systems, the data and telecommunication systems, etc. Road network vulnerability can thus be seen as a special case of infrastructure vulnerability, and the interpretation of vulnerability should be much the same for all these systems.

Unfortunately, there is no widely accepted 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), Haimes (2006), Aven (2007) and Ezell (2007). I will not attempt a full literature review of the vulnerability concept here; a further discussion is found in Paper I.

The view on vulnerability that I will adopt here is similar to that of Berdica (2002), who defines vulnerability for the road transport system as "a susceptibility to *incidents* that can result in considerable reductions in road network *serviceability*". The serviceability of a link/route/road network, in turn, is defined as "the possibility to use that link/route/road network during a given time period", and an incident is "an event, which directly or indirectly can result in considerable reductions or interruptions in the serviceability of a link/route/road network". This definition is easily generalized, by suitable interpretations of serviceability, to other infrastructures as well.

The technical infrastructures have in common that they provide services that are critical to the society (hence the term critical infrastructure). In fact, their main purpose is to provide these services, and if they cannot be provided because of a reduction in the performance of the system, the infrastructures are of little other value[5]. The consequences for the users if the performance is reduced, however, will likely be severe. Therefore, I argue that infrastructure vulnerability should first and foremost be seen from a demand rather than a supply perspective, and the focus should be on the users rather than the system itself. In other words, the vulnerability of an infrastructure should be seen as the vulnerability of its users.

With a more user-centered perspective, we can define the vulnerability of a user as a susceptibility to incidents that can result in considerable reductions in user *service*. This definition can be expanded to groups of users, for example households or companies, or based on geographic location, economic status, gender, etc., up to the group all users.

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[5] In the case of privately operated infrastructures, another purpose is of course to yield profit to the owners.

3.1 Vulnerability and exposure

In vulnerability analysis we consider incidents—initial events that may be internal or external to the system, and also unintentional (random) or intentional—that lead to reductions in the performance of the system, which in turn leads to consequences for the users. The analysis chain can thus be broken up into two stages: i) assessing the likelihood of various incidents that may reduce the performance of the system, and ii) assessing the consequences of the reduced system performance for the users. This Thesis is almost exclusively concerned with the second stage, which we may call *conditional* vulnerability analysis (i.e., conditional on that the system performance is reduced).

To facilitate the analysis, Paper I introduces the concept of *exposure*, and defines the exposure of a user to a specific reduction in system performance as the reduction in user service that follows from the performance reduction. Exposure can thus be seen as conditional vulnerability from a demand perspective, and just as with vulnerability we can study the exposure of individual users, groups of users or the whole society. It should be noted that Taylor and D'Este (2004) and Taylor et al. (2006) use the term vulnerability for essentially the same concept.

To be concrete, the type of performance reduction considered throughout this Thesis is a complete closure of a particular or randomly chosen road link (i.e., a road segment between two junctions) for a given time period. However, one can just as well consider exposure to more complicated events, such as a partial reduction of the capacities of the roads in a particular geographic area, which may follow from, say, a snow storm.

In Paper I we group travellers based on in which municipality they live, and define the exposure of the municipality to be the average exposure of the users in the region. We study the municipal exposure for two types of performance reductions: i) a worst-case scenario where the road link causing the largest consequences for the users in the region is closed, and ii) an average-case scenario where we calculate the expected consequences of closing a randomly chosen link in the road network. This geographical exposure analysis is further refined in Paper II.

3.2 Criticality and importance

As stated in Section 2, an important part of infrastructure vulnerability analysis is to identify points, components or regions—here collectively called "elements"—in the system where incidents would lead to severe consequences for the users, and where the likelihood for such incidents must be considered significant. Following Nicholson and Du (1994), such elements are said to be *critical* for the serviceability of the infrastructure. As with vulnerability in general, the identification of critical elements involves two stages: i) identifying and assessing the likelihood of incidents that may cause an performance reduction of a particular element, and ii) assessing the consequences of the reduced element performance for the users. Again, we will focus on the second stage of this process in the Thesis.

For this purpose, we define the *importance* of an infrastructure element (given a specific type of performance reduction) to be the reduction in overall user service that follows from a performance reduction (of the specified type) of that element. Importance can thus be regarded as *conditional* criticality, a relation that has been adopted from Nicholson and Du (1994).

We condition the definition of importance on a "specific type of performance reduction" because system elements may have several functions, and also because we want to consider different durations of the performance reduction. The kind of elements considered in this Thesis are exclusively single links in the road network, and the type of performance reduction considered is a complete closure of the link for a given duration of time.

The difference between exposure and importance, and between vulnerability and criticality, is a difference in perspectives. Whereas exposure is concerned with how a particular user or group of users is affected by performance reductions in the infrastructure, importance is concerned with how a performance reduction of a particular infrastructure element affects the users. Thus, importance and criticality represents an *operator* perspective rather than a user perspective. For the operator it is a much more direct action to reduce the importance of an element than to reduce the exposure of a group of users. We will return to this observation in Section 6.

Just as with vulnerability, there are differing notions in the literature of what criticality and importance is. Taylor et al. (2006) defines criticality roughly as I here define importance; other terms for the same concept include significance (Sohn, 2006) and vitality (Ball et al., 1989). The term importance is also used, with a different meaning, in reliability theory.

3.3 Risk, robustness and resilience

There are a few concepts related to vulnerability that we should briefly consider. *Risk*, as the term is normally used in risk analysis, can be described as a combination of an event with negative consequences for human life, health or environment and the probability for this event[6]. The risk and vulnerability concepts thus have many similarities, but also differences. First, risk analysis is concerned with "random", unintentional events (*hazards*) such as technical failures and forces of nature, whereas vulnerability analysis also considers intentional attacks (*threats*). Second, risk analysis considers impacts on health and environment that may be external to the analyzed system, whereas vulnerability analysis considers impacts on the serviceability of the system itself. If risk is defined strictly as the product of probability and consequence, which it sometimes is, another difference is that vulnerability analysis should not neglect scenarios with severe potential consequences, even if the probability for the scenario is deemed very low. However, with a broader view on risk including all kinds of incidents and consequences, vulnerability analysis can be seen as a particular form of risk analysis.

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[6] The risk term is also used in other fields, e.g. economics, but we will not look deeper into the different uses here.

Robustness is generally seen as the ability of a system to retain its function when it is under strains, while *resilience* is the ability to recover to a normal state after having been disturbed. Robustness and resilience are thus properties of the system itself, excluding the external environment. In view of how we have defined vulnerability, vulnerability implies a lack of robustness and resilience, but not necessarily vice versa. For an infrastructure to be vulnerable we also require that there are incidents of some likelihood, internal or external to the system, that have the capacity to put the system under strains. Instead, we may see robustness and resilience as being the converse of *conditional* vulnerability.

3.4 Reliability

Reliability is, with a widely accepted definition, the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered. 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 (see further Høyland and Rausand, 1994).

Reliability theory is used heavily for technical infrastructures such as the electric power system. For the road transport system, reliability has recently become a field of much research. Within the transport setting, reliability is typically defined as the probability that the transport system performs above some predefined level of serviceability. A number of different reliability measures based on different serviceability indicators have been proposed. One of the earliest and simplest measures 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 (see, e.g., Wakabayashi and Iida, 1992; Bell and Iida, 1997). More refined reliability measures that have been introduced include travel time reliability, which is the probability that a trip can be finished within a specified time interval (see, e.g., Bell and Iida, 1997; Yang et al., 2000) and capacity reliability, defined as the probability that a network can accommodate a specified level of travel demand (see, e.g., Yang et al., 2000; Chen et al., 2002).

By definition, transport reliability is concerned mainly with probabilities of different disturbances and little with the magnitude of the consequences. Reliability analysis is thus more narrow than vulnerability analysis, and can be seen as a component of the latter. The methodology is still in the developing stages, but should in general be especially suitable for lighter, more frequent disturbances such as recurrent congestion, minor accidents, construction works, etc.

4 Quantitative vulnerability analysis

With quantitative vulnerability analysis we aim to express the consequences and likelihood of a scenario in numbers rather than just qualitatively in words. This can be done, at least theoretically, in a number of ways. Ideally, we could perform experiments or controlled observations of the mechanisms behind an incident and the following responses and impacts on the users. In practice, this is of course unfeasible for ethical, technical and economical reasons.

One approach to estimating the likelihood of different kinds of incidents is to study historical data with statistical methods. Some studies of this type have been performed for the road transport system; e.g., Golob et al. (1987) and Giuliano (1989) analyze frequencies and durations of car and truck accidents. In order to assess the consequences of incidents, however, it is almost inevitable to use some form of model-based analysis of the transport system. Of course, what model should be used to perform the analysis will depend on how the consequences are measured.

4.1 Operationalizing consequences

To capture the negative social and economic impacts of incidents on people and businesses in one or a few quantitative measures is a difficult task. We must probably accept that no measure is able to capture the relevant impacts of every kind of incident. However, the measures that we use may serve as *indicators* and approximations of the more complex aspects of the real world.

For short-term disturbances, it may be safe to assume that most trips and transports will be carried out as planned, and the costs associated with the disturbance will mainly be due to the increases in travel time and delays for the users. For long-term disturbances, beside changing routes, people may adjust to the reduced performance by e.g. cancelling some trips and changing destination or travel mode for others. As a result, their *accessibility*, i.e. their ability to take part in activities (work, school, daycare, medical care, shopping, entertainment, etc.) in other locations, will be reduced.

Measuring the reduced accessibility should be a good way to evaluate the reduced transport service for people, and most quantitative vulnerability studies in the literature use some kind of accessibility-based consequence measure. The simplest indicator of reduced accessibility is the increase in travel time to the original travel destinations, which subsequently may lead to a new travel pattern. More generally, one can study the increase in *generalized travel cost*, where other restricting factors such as travel distance and monetary costs are also included.

The increase in travel time is used as consequence measure throughout this Thesis. Similary, 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.

Taylor et al. (2006) identify exposed nodes and important links in the Australian national transport network and a small regional road network. The authors note that different applications call for different consequence measures, and they use three different measures of diminished accessibility: the increase in generalized travel cost, the relative decrease in the Hansen integral accessibility index (inversely proportional to the generalized travel cost), and the increase of a “remoteness” index specially developed for the regional and remote parts of Australia.

Sohn (2006) proposes an accessibility index that incorporates road distance and traffic volumes and uses it to assess the importance of highway links in Maryland, USA, under flood damage. The importance of a link is measured as the total decrease in this accessibility index when the link is closed. Chen et al. (2007) calculate the long term effects of a closure of one or more links in a road network as the decrease of a utility-based accessibility measure.

For businesses, the natural way to evaluate the consequences of system performace reductions is to measure the economic losses. As companies may e.g. switch suppliers and cancel deliveries to adjust to the reduced performance of the transport system, the economic impacts can be very complex. Again, the increase in travel time or generalized transport cost should provide some indication of these losses.

4.2 Model-based analysis

Transport models have long been used for different purposes, ranging from assessing the long-term effects of transport policy changes or infrastructure investments, to optimizing the logics of traffic lights. Virtually all used transport models are based on network representations of the transport system, with nodes representing trip origins/destinations and junctions, and links representing road segments. As far as I know, however, no models have been developed specifically for vulnerability or reliability analysis; furthermore, no existing model is really suitable for evaluating the consequences of every kind of incident. What modelling approach should be used then depends on the setting for the analysis: the kind of road network (rural, urban, etc.), the kind of performance reduction (single link closure, major area closure, etc.), the duration of the disturbance, the type of affected users (households, companies, etc.), and so on.

In regions with dense traffic, the effects of queueing, limited information and disorder during short-term disturbances will likely be significant. This suggests the use of a dynamic model that is able to describe the time evolution of the traffic. The most detailed models, the so-called *microscopic* models, simulate the journeys of individual vehicles through the network. Knoop and Hoogendoorn (2007) use micro-simulation to study the effects of blocking links in the congested urban network of Rotterdam. They find that modelling queue spillback properly is crucial for correctly identifying the most important links.

A disadvantage of microscopic models is that they require detailed data about the transport system and careful calibration of a large number of parameters with complicated relations, and they are computationally very time and memory demanding. Therefore, microsimulation models are generally used only on geographically limited regions, in particular parts of urban road networks.

If the duration of the disturbance is considerable, the transport system should after some time settle in a state where all users have found the best way to adjust to the reduced performance. The reductions in user service can then be evaluated by comparing the new equilibrium state with the equilibrium state before the disturbance, and a static transport model should be sufficient. The advantage of static models in vulnerability analysis is that travel times and accessibility measures can be calculated relatively fast even for large networks, especially if no congestion effects are considered. The disadvantage is that the equilibrium assumption may be far from the truth for relatively short-term disturbances, where the initial disorder can be a large factor in the overall service reduction. Therefore, the models may underestimate the true consequences due to short-term incidents. Still, because of their computational tractability, models of this kind are used throughout this Thesis and in most vulnerability studies in the literature.

Taylor et al. (2006), Scott et al. (2006) and Sohn (2006) all use static models with or without congestion to calculate their consequence measures. 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. In one of few studies focusing on the business community, Ham et al. (2005) use a combined multimodal transport network and interregional commodity flow model to assess the long term economic impacts of a number of earthquake scenarios in the New Madrid Seismic Zone, USA.

As noted above, none of the transport models presently in use seems to have been developed with vulnerability or reliability analysis in mind. Berdica et al. (2003) study the consequences of the same incident scenario with three different models 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”. We will return to this problem of validity in Section 7.

5 Contributions of the Thesis

5.1 Paper I: Importance and exposure in road network vulnerability analysis

Paper I represents one of the first attempts in the literature to quantitatively study the vulnerability of a full-scale real-world road network. Similar ideas had been presented by Taylor and D’Este (2004), but without any case study application.

In this paper we introduce exposure and importance as two fundamental concepts in vulnerability analysis. Following Nicholson and Du (1994), the *importance* of a link is defined as the consequences when the link is completely closed. *Exposure* is studied on a regional level and is defined as the consequences for the users in the region given a certain scenario. Two scenarios are studied: a “worst-case” scenario where the most important link for the region is closed, and an “average-case” scenario where a randomly chosen link in the network is closed. Both exposure and importance are studied from two basic perspectives; from the “social efficiency” perspective, we measure the average increase in travel time per traveller, given that he/she makes the same trip as without the link closure. From the "equal opportunities" perspective, we study the consequences for the possibility to make an arbitrary trip, as measured by the average increase in travel time per origin-destination (OD) pair.

There is a possibility that closing a link means that some travellers have no way to reach their destination. The average increase in travel time when such a *cut link* is closed is therefore infinite, which causes problems when comparing them with other links. To measure the consequences of closing a cut link, we introduce the concept of *unsatisfied demand*, defined as the number of travellers who are unable to reach their destination.

The various exposure and importance measures are applied to the road network of northern Sweden. Since the traffic load on the roads in the area is generally very low, the measures are calculated with a time efficient static transport model without congestion. Regarding link importance we find that from the equal opportunitites perspective, the most important links are sections of the main road in the area, the E4 European highway along the coast. From the social efficiency perspective, the most important links are parts of the E4 going through the main population centres in the area.

Regional exposure is studied at the municipal level. Among the results may be noted that for the average-case scenario from the social efficiency perspective, some of the municipalities along the Norwegian border, where both the population and the road network are particularly sparse, are the most exposed ones. When unsatisfied demand is considered, however, the northernmost municipality of Kiruna is the most exposed. This illustrates that these two measures should not be studied in isolation from each other. The results are similar for the worst-case scenario.

5.2 Paper II: Spatial patterns of road network vulnerability

Paper II refines the methodology and deepens the analysis of Paper I. The focus is here on regional importance and average-case exposure from a socio-economic efficiency perspective. *Regional importance* is defined as the expected overall increase in user travel time when a randomly chosen link in the region is closed. *Regional exposure* is further divided into two measures: i) *user exposure* (called simply "exposure" in Paper I), the average increase in travel time per user starting in the region, and ii) *total exposure*, the total increase in travel time for all users whose trips are starting in the region. For both importance and exposure, the probability of closing a particular link is proportional to the length of the link.

The analysis method from Paper I is improved to include both cut links and non-cut links in a single measure, eliminating the need for the unsatisfied demand measure. This is done by considering an explicit closure duration and assuming that users with no alternative routes during the closure will wait until the link is reopened to make their trip. Again, no congestion effects are considered, which likely underestimates the impacts in the major cities.

The regional exposure and importance measures are applied to the municipalities and counties in the whole of Sweden in a case study with two basic purposes: to investigate how the the exposure and importance differ between different regions in Sweden, and to identify properties of the geography, network and travel patterns that can help explain these differences.

Regarding regional user exposure the findings are in line with those of Paper I: the most exposed municipalities are located in the mountainous areas in the northwest of Sweden, whereas the southern parts are considerably less exposed. The total exposure, on the other hand, follows the population quite well, so that the main population centres are the most exposed municipalities. Regarding regional importance, many of the most important municipalities are located around Stockholm, and the efficiency of the transport system is highly dependent of the road networks in these municipalities. We also find that the regional disparities in exposure and importance increase with the duration of the closure.

Using statistical regression analysis, we find that the observed regional differences in user exposure, total exposure and importance to a large extent can be explained by two factors in each case. For all three measures, the sparsity of the road network in the region is of great significance. For user and total exposure, the initial average and total travel time, respectively, of the users in the region are also influential factors, whereas for importance the average link flow in the region has greater explanatory power. These simple relations can help us estimate the exposure and importance of a region without extensive calculations. They also hint at what measures can be taken to reduce the exposure or importance of a region.

5.3 Paper III: Considering the user inequity of road network vulnerability

Paper III looks further into the issue of the disparities and inequities of road network vulnerability, and presents a method to quantify the importance of road links based not only on the overall consequences but also on the disparities among the users. Thus, it extends the work of Paper II by measuring inequity at the user rather than regional level, and by considering each link separately rather than studying an average-case scenario. The same travel time model as in Paper II, which does not consider congestion effects, is used to calculate the consequences of a link closure.

We propose an importance measure that is a weighted product of the total increase in user travel time (equivalent to the “efficiency” importance in Paper I) and the inequity of the distribution, as measured by the coefficient of variation among the users. By adjusting the weight parameter, the transport planner can control how much influence equity considerations should have on link importance. We show analytically that there is a strong inverse relationship between the efficiency and the equity components.

In a case study of the Swedish road network we show that when pure efficiency importance is considered, links in many of the main roads, in particular the European highways, are among the most important. With more weight put on equity, importance is gradually shifted to smaller local roads with poor or no alternative routes. These results tell us that if we are only concerned with the overall efficiency of the road transport system, we should focus our attention to the largest and most busy roads, but if we are also concerned with user equity, more attention must be given to certain local roads.

6 Discussion: vulnerability analysis in practice

In Section 2, I pointed generally to the value of road network vulnerability analysis. I will here discuss more specifically the value of the three papers in the Thesis and how the presented measures can be used in practice.

To begin with, Paper I introduces two perspectives on the consequences of a road closure. From a socio-economic perspective, we consider the consequences for each trip, given that all trips are made as they would be without the closure. From an equal opportunities perspective, we consider the consequences for each OD pair, corresponding to a reduced possibility to make an arbitrary trip. While the latter perspective provides useful insights, I think that the former should be the dominating focus of vulnerability analysis, since it is more strongly connected to the actual social and economic impacts of an incident. In Paper II, and particularly Paper III, the socio-economic view is further divided into aspects of efficiency versus equity.

Furthermore, the Thesis establishes that vulnerability can be seen from another pair of perspectives, those of the user and the operator. From the user perspective, we study regional exposure to average-case and worst-case scenarios, to identify regions that are—at least potentially—particularly severely affected by link closures. From the operator perspective, we study link importance to identify road links that will have particularly severe consequences for the users if any of them are closed. In Paper II, we also generalize link importance to the importance of a region in the road network.

The regional exposure measures give us a general idea of the vulnerability in different parts of the road network. User exposure tells us how an average individual user will be affected by a disturbance, whereas total exposure (introduced in Paper II) tells us how the region as a whole will be affected. Total exposure should thus be of interest for the regional authorities with an interest in the overall efficiency of their region.

From an operator perspective, it is difficult to determine how to best reduce regional exposure. To begin with, one has to decide on what kind of scenarios to consider; then, one must identify actions that can reduce the consequences of the considered scenario, which may not be self-evident. It is important to realize that the geographical variations in exposure are caused by structural differences in the country that cannot be changed by a few infrastructure investments. That people in sparsely populated areas are particularly exposed is of course due to the fact that it is not socio-economically defendable to operate as dense road networks there as in densely populated areas. What the regional exposure measures can contribute with, rather, is a well-informed basis for the general long-term balancing between socio-economic efficiency and regional development in the road transport system. These are both goals of the official Swedish transport policy. At this strategic level, the exposure measures are complemented by the regional importance measure, which suggests in what regions reinforcements of the road network would reduce the overall consequences of road closures the most.

In terms of practical usefulness, link importance should be of the greatest immediate benefit of the studied measures. For the decision-maker, the link importance measures gives a very direct way to identify actions that as effectively as possible reduce the socio-economic costs of road disruptions. A road link is a well-defined and geographically bounded unit that is easily targeted with vulnerability-reducing actions, and should therefore constitute a suitable level of analysis.

With the equity-weighted importance measure introduced in Paper III, we can cover both efficiency and equity considerations simultaneously when identifying the most important links. This means that a road link with a highly inequitable distribution of impacts when disrupted may well be considered more important than one with slightly greater but more evenly distributed impacts. Since the decision-maker can adjust how much weight is to be put on the equity aspect, this makes it arguably the most directly valuable one of the measures introduced in the Thesis.

Of course, a limitation of concentrating on link importance is that we ignore the potential of more than one link being closed simultaneously. This is a very realistic consequence of geographically wide-spread events such as floods, thaw and heavy snowfall. Two links may not be important when each is considered individually, but if both are closed the consequences may be considerable. Hence, there is still a need for an eyes-open approach to vulnerability analysis, and for considering more complex scenarios than single link closures.

7 Issues for the future

As the reader may have noted, there is still much research to be done in order to develop the methodology for road network vulnerability analysis. I conclude this first part of the Thesis by noting a few areas where further work should be worthwhile, either to improve or to complement the work presented here.

Tie vulnerability to socio-economic assessments. Is it meaningful to try to reduce vulnerability, and if so, how much resources should be spent for that purpose? These fundamental questions still lack definitive answers, and to find some, vulnerability must be brought into the same framework as the other important aspects of the road transport system, issues such as traffic safety, accessibility and sustainability. It is important to note that the aim of reducing vulnerability may be in conflict with other important goals, such as reducing the environmental impacts of the transport system. In order to include vulnerability issues in the planning process, they must be associated with concrete cost assessments.

Develop the probability part of vulnerability. For a full valuation of road network vulnerability, we need a comprehensive assessment of likelihoods for all kinds of scenarios. This will likely require an array of different approaches. We should relatively easy be able to roughly identify roads that are likely to be affected by e.g. traffic accidents (because of heavy traffic, narrow verges etc.), floods (proximity to water, rain afflicted areas, etc.), land slides (soil type, rain, etc.) and heavy snow. For a more precise assessment, however, it is necessary to perform surveys of each individual road in order to identify features that make the road liable to disruptions (underdimensioned drain pipes, wear and tear damage, danger of rockfall, etc.). In Sweden, work in this area is underway, as described by e.g. Klimat- och sårbarhetsutredningen (2007), and particular types of incidents have been modelled mathematically or studied statistically in the literature. A synthesis of the existing work is needed.

Develop the consequence models. To better estimate the service reductions for people and businesses due to road network performance reductions, the models should ideally be improved in several directions. First, as noted in Section 4, there is a problem of validity since the used models were not designed to handle unexpected disturbances. This should be investigated further, and if needed, new models may have to be developed.

Second, the presently used models only allow for relatively rough consequence measures such as the increase in travel time or derivatives thereof. One possibility may be to take the approach of Chen et al. (2007), who propose a full travel demand model to assess the effects of a disturbance in terms of the decrease of a utility-based accessibility measure. This method makes very strong assumptions of equilibrium, however, and is suitable only for very long-term disturbances. Another approach, which I think is still untried, is to use an *activity-based* model. Instead of just generating single trips, activity-based models generate chains of trips starting at home in the morning, via daycare drop-offs and pick-ups, workplace commuting, shopping tours, etc., returning home in the evening. Hence, they have a potential to more truthfully capture the impacts of disturbances in the transport system.

Of course, in strong conflict with the wish for more detailed models is the wish to analyse large road networks and hence the issues of computation times and data collection. It remains to be seen where the compromise between these wishes needs to be made.

Study the restoration process. The previous two points in this section address the questions “What are the consequences?” and “How likely is it to happen?” that were formulated in Section 2 and borrowed from Holmgren (2007). There is also a need to address the fourth question, “How is a normal state restored?”. More precisely, we need to determine how to organize and locate resources for restoring the transport system after a disturbance as efficiently as possible. A quick restoration process is critical for limiting the impacts of an incident, which otherwise should increase rapidly with the duration of the disturbance.

Study the vulnerability of freight transport. So far, the focus of most vulnerability studies in the literature has been on personal trips. For heavy transports, an additional complication is that the bearing capacities of the roads put strong restrictions on which routes can be taken. Hence, the closure of a road with high bearing capacity may lead to very long detours for freight transports. This justifies that the vulnerability of freight transport should be given special consideration.

Develop area-based scenario analysis. As discussed in Section 6, by only studying single link closures we run the risk of overlooking vulnerabilities involving multiple link closures. To be able to model scenarios that affect an entire area, e.g. a snow storm, one possibility would be to divide the study area into squares or hexagons of equal size, where each polygon represents the extent of the event to be modelled. For each polygon, the road links that intersect it are closed and the service reductions are calculated. This gives an image of where in the study area an event of this extent would have the most severe consequences. With information on the likelihood of the particular event in different parts of the study area, some polygons can be given higher weights in the results.

Evaluate the consequences of climate change. According to the commission assigned to investigate the consequences for Sweden of the changing climate, the likelihood of floods, landslides and erosion damaging the road network will increase in the future (Klimat- och sårbarhetsutredningen, 2007). Thus, there is a strong need to study in more detail where these events are most likely to occur and what the consequences for the society will be. A concrete example would be to identify low bridges in regions where floods will become more frequent. If several bridges along the same watercourse would be flooded, the impacts on society could be enormous.

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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.

Bell, M. G. H. and Iida, Y. (1997) *Transportation Network Analysis*. Chichester, West Sussex: Wiley.

Berdica, K. (2000) Analysing Vulnerability in the Road Transportation System – Putting Theory into Practice Using Sweden as an Example. Licentiate thesis, Royal Institute of Technology, Stockholm, TRITA-IP FR 00-76.

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.

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.

Einarsson, S. and Rausand, M. (1998) An approach to vulnerability analysis of complex industrial systems. *Risk Analysis* 18, 535–546.

Ezell, B. C. (2007) Infrastructure vulnerability assessment model (I-VAM). *Risk Analysis* 27, 571–583.

Giuliano, G. (1989) Incident characteristics, frequency, and duration on high volume urban freeway. *Transportation Research* 23A, 387–396.

Golob, T. F., Recker, W. W. and Leonard, J. D. (1987) An analysis of the severity and incident duration of truck-involved freeway accidents. *Accident Analysis and Prevention* 19, 375–395.

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.

Holmgren, Å. J. (2007) A Framework for Vulnerability Assessment of Electric Power Systems. In Murray, A. T. and Grubesic, T. H. (eds), *Critical Infrastructure: Reliability and Vulnerability*, Advances in Spatial Science. Springer, 31–55.

Høyland, A. and Rausand, M. (1994) *System Reliability Theory: Models and Statistical Methods*. New York, NY: John Wiley & Sons.

Jämtlands läns landsting (2006) Raset vid Ånn: Sjukvården fungerar som vanligt igen. Press release 02/08/2006, in Swedish.

Klimat- och sårbarhetsutredningen (2007) Sverige inför klimatförändringarna – hot och möjligheter. Miljödepartementet, SOU 2007:60, in Swedish.

Knoop, V. and Hoogendoorn, S. (2007) The need of spillback simulation in assessing robustness: Concepts and a case study with dynamic route choice. Presented at the Sixth Triennial Symposium on Transportation Analysis (Tristan), Phuket Island, Thailand, June 10–15 2007.

Länstidningen Östersund (2006a) E14 öppen för trafik igen. *Länstidningen Östersund* 01/08/2006, in Swedish.

Länstidningen Östersund (2006b) Marken rämnade under rälsen. *Länstidningen Östersund* 31/07/2006, in Swedish.

Länstidningen Östersund (2006c) Slutnotan för raset på E14 blir minst 18 miljoner. *Länstidningen Östersund* 06/09/2006, in Swedish.

Länstidningen Östersund (2006d) Tågstopp och bandvagnar efter vägras. *Länstidningen Östersund* 31/07/2006, in Swedish.

McEntire, D. A. (2005) Why vulnerability matters: Exploring the merit of an inclusive disaster reduction concept. *Disaster Prevention and Management* 14, 206–222.

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.

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.

Sohn, J. (2006) Evaluating the significance of highway network links under the flood damage: An accessibility approach. *Transportation Research Part A* 40, 491–506.

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.

Vägverket (2006a) E14 öppnas för all trafik redan i dag fredag klockan 13.00. Press release 11/08/2006, in Swedish.

Vägverket (2006b) E14 öppnas för provisorisk personbilstrafik idag kl 19.00. Press release 01/08/2006, in Swedish.

Vägverket Produktion (2006) Rekordsnabb återuppbyggnad av E14. Press release 14/08/2006, 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.

Willis, H. H. (2007) Guiding resource allocations based on terrorism risk. *Risk Analysis* 27, 597–606.

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.