

# Road network vulnerability: Identifying important links and exposed regions

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## ABSTRACT

The reliability and vulnerability of critical infrastructures have attracted a lot of attention recently, also concerning road networks. In order to assess these issues quantitatively, operational measures are needed. Such measures can also be used as guidance to road administrations in their investment planning and in their prioritisation of maintenance and repair of roads, as well as for avoiding causing unnecessary disturbances in the planning of roadwork. The concepts of link importance and site exposure are introduced. Several indices of link importance and site exposure are derived, based on the increase in generalised travel cost when links are closed. The measures are calculated for the road network of northern Sweden. Results are presented per link and municipality.

## 1. Introduction

Given the importance of the transport networks for journeys to work, for production logistics (notably the *just-in-time* philosophy), and for business travel, the reliability and vulnerability of transport networks are key issues from the point-of-view of transport system users and hence planners at all levels, both in the public and private sectors. For the purpose of road management, prioritisation for road investment, maintenance and repair, contingency planning, and for the assessment of regional disparities, it would thus be helpful with a general “vulnerability index” attached to links and nodes.

In incident and contingency planning, and in the planning of road works, there should be an awareness about the impacts of reduced capacity on links. Increased efforts to avoid capacity reductions should be made on links that are more critical to the system. Similarly, increased awareness is called for about the degree of vulnerability in different places in the system, and more efforts should be directed towards reducing it. In view of the strategic goals of the Swedish Road Administration (SRA) of a “positive regional development” and “an accessible transport system”, relevant questions to ask are: “Which regions are most susceptible to disruptions in the transport system?” and: “Which links are most critical to the operation of the whole system?”. In order to make such distinctions, general measures of the criticality of links in the network, and the vulnerability of sites, municipalities etc. need to be developed and tested.

## 2. Definitions of concepts

The concept of vulnerability does not have a firm and commonly accepted definition for all circumstances, but has to be defined depending on the context. In a road network context,

Berdica (2002) defines vulnerability as “a susceptibility to incidents that can result in considerable reductions in road network *serviceability*”. The serviceability of a link/route/road network “describes the possibility to use that link/route/road network during a given period”. Instead of serviceability, the terms performance, capacity and operability have been used in the literature. Other authors stress the sudden, unpredicted or infrequent occurrence of the events (see, e.g., Swedish Department of Defence, 1998). This reveals the dual characteristic of the concept: it has one component of probability and one of consequence. Normally, these components go hand in hand in an inverse relationship, so that the greater the consequence, the more rare is the event that triggers it. The part of the vulnerability concept that is only related to the consequence, we call *exposure*.

The criticality of a component (link, node, groups of links and/or nodes) is related to the vulnerability of the system in the way that the more critical the component, the more severe is the damage to the system when it is lost. Criticality can be decomposed in the same way as vulnerability; in accordance with Nicholson and Du (1994), we call a component *weak* if the probability of an incident is high, and *important* if the consequences are great. To be called *critical*, the component has to be *both* weak and important.

We argue therefore that when trying to measure vulnerability or criticality, they should be dissociated into these two components. Depending on the context, it is more relevant to focus on one or the other. In this study, we focus only on the consequences, i.e., on what the reductions in performance will be, given that there is an incident.

### 3. Model and measures

As a measure of reduced performance of the network, we use the increase in generalised cost of travel (time, distance, money, etc.) for a user of the network. We assume here that the incident is a single link being completely disrupted or closed, which forces all travellers using that link to take other, less advantageous routes<sup>1</sup>. The travellers are assumed to behave according to the user equilibrium principle, i.e., they choose a route from their origin to their destination that minimises their travel cost. Our approach is similar to the one outlined in Taylor and D’Este (2004). Let us introduce the following notation:

$E$	The set of all links in the network.
$E^{\text{nc}}$	The set of <i>non-cut links</i> , i.e., links that do not isolate any nodes in the network when closed.
$V_m^{\text{d}}$	The set of <i>demand nodes</i> , i.e., origin/destination (OD) nodes, in municipality $m$ .
$c_{ij}^{(0)}$	The generalised cost of travel from node $i$ to node $j$ in the initial, undamaged network.
$c_{ij}^{(k)}$	The generalised cost of travel from node $i$ to node $j$ when link $k$ is closed.
$x_{ij}$	The travel demand from node $i$ to node $j$ .

When a link  $k$  is closed, the network may be divided into several disconnected parts. The travel costs between nodes in different parts then become infinite. Instead, we measure the number of trips from  $i$  that are unable to reach  $j$  due to the closed link  $k$ . For this event we introduce the concept of *unsatisfied demand*  $u_{ij}^{(k)}$ , defined as

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<sup>1</sup> The idea can easily be extended to the failure of more than one link. The failure of a node can be seen as being equivalent to the failure of all links connected to the node.

$$u_{ij}^{(k)} = \begin{cases} x_{ij} & \text{if } c_{ij}^{(k)} = \infty, \\ 0 & \text{if } c_{ij}^{(k)} < \infty. \end{cases}$$

Consider first a non-cut link  $k$ . To calculate the *importance* of link  $k$  for the whole network, we aggregate the travel cost increase  $c_{ij}^{(k)} - c_{ij}^{(0)}$  over all OD pairs. If the travel demand  $x_{ij}$  is used as weight, the severity of an increase in travel cost between two nodes depends on the traffic between them. This measures the capability of the road system to provide socially and economically efficient transports where the demand is the highest. The demand weighted importance of link  $k$  with regard to the whole network is then

$$\text{Importance}_{\text{net}}^{\text{dem}}(k) = \frac{\sum_i \sum_{j \neq i} x_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} x_{ij}}, \quad k \in E^{\text{nc}}.$$

Correspondingly, the importance pertaining to unsatisfied demand of any link  $k$  with regard to the whole network (relative to total demand) is

$$\text{Importance}_{\text{net}}^{\text{uns}}(k) = \frac{\sum_i \sum_{j \neq i} u_{ij}^{(k)}}{\sum_i \sum_{j \neq i} x_{ij}}, \quad k \in E.$$

When measuring the increase in travel cost for a *municipality*  $m$ ,  $c_{ij}^{(k)} - c_{ij}^{(0)}$  is aggregated over all origins  $i$  in the municipality and all destinations  $j$  in the entire network. One event is the failure of the *most important link* for the municipality. This “worst-case” scenario would correspond to an attack by an informed terrorist who wishes to cause as much damage as possible to municipality  $m$  with only one strike. The *demand-weighted exposure* of municipality  $m$  is then the maximum value over all non-cut links,

$$\text{Exposure}_{\text{max}}^{\text{dem}}(m) = \max_{k \in E^{\text{nc}}} \frac{\sum_{i \in V_m^{\text{d}}} \sum_{j \neq i} x_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_{i \in V_m^{\text{d}}} \sum_{j \neq i} x_{ij}}.$$

The exposure pertaining to unsatisfied demand of each municipality is correspondingly

$$\text{Exposure}_{\text{max}}^{\text{uns}}(m) = \max_{k \in E} \frac{\sum_{i \in V_m^{\text{d}}} \sum_{j \neq i} u_{ij}^{(k)}}{\sum_{i \in V_m^{\text{d}}} \sum_{j \neq i} x_{ij}}.$$

## 4. Case study: the road network of northern Sweden

### 4.1 Network and travel data

We have used these measures in a case study of the road network of northern Sweden (the counties of Dalarna, Gävleborg, Västernorrland, Jämtland, Västerbotten and Norrbotten). This is geographically the larger part of the country, but at the same time the most sparsely populated part. There are two main roads going in the north-south direction: the E 4 European highway following the coast and the inland national road 45. Along the rivers, the European highways E 10, E 12 and E 14 and a few national roads are going in the north-west-to-south-east direction, starting in Norway and ending on the Botnian Sea coast.

The network and travel data are extracted from the Swedish national travel demand model system SAMPERS (Beser and Algiers, 2001) as implemented by the Swedish Road

Administration. The travel demand is measured in number of vehicles as an annual daily average. The vehicles include personal cars for private and company use, personal cars in commercial traffic, and heavy trucks with and without trailer. The travel time between the demand nodes is used as the generalised cost of travel. We assume that the travel times are independent of the traffic flow on the links. This approximation should be reasonable for the network we study, since the region is sparsely populated and most links have fairly low initial traffic flows. It allows us to use a simple and fast algorithm to find the fastest routes between origins and destinations for the initial network and when a specific link is closed (Dijkstra, 1959). The travel time of each link is obtained by dividing its length by the free-flow speed from the volume-delay function in the SAMPERS model.

A fuller discussion of the assumptions of the model and the case study can be found in Jenelius et al. (2006).

## **4.2 Results**

### *4.2.1 Link importance for the whole network*

The demand-weighted importance of each link is the increase in travel time per trip when the link is closed. The most important links are generally short roads within cities. In particular, many of the links are parts of the E 4 going through Gävle and Umeå, two of the three largest municipalities in the area. These road sections therefore accommodate both regional and local traffic. The most important link is located in the city of Gävle to the south. When closed it causes an increase in travel time by more than one minute calculated as an average per all performed trips in the northern Sweden. However, these results should be treated with some caution since the network data does not include all the small streets in the cities. The effects of closing a city street may therefore appear more severe than they would be in reality. On the other hand, smaller streets are not generally known to all drivers.

Similarly, the links that cause the largest relative amount of unsatisfied demand when closed are generally short roads in or near cities. In particular, many of the links are located east of the E 4, close to the coast where there is little room for alternative links. When the most important link, again located in Gävle, is closed, nearly one in every forty vehicles is unable to reach its destination. Since also this measure is sensitive to inaccuracies in the network data, the results should not be taken too literally.

### *4.2.2 Municipality exposure*

The demand weighted exposure of a municipality is the increase in travel time per trip that begins in the municipality and ends anywhere in the network. Since most demand is to nearby destinations, the effects of closing a link is quite local, and the most important link is always located within the same municipality. The situation is the worst in the north-western region, where the local road networks are sparser, with fewer good alternatives, than elsewhere. In Arjeplog the travellers will experience an average increase in travel time by almost one and a half hour when a certain link is closed (Table 1).

Several of the most densely populated coastal municipalities are highly exposed regarding the relative amount of unsatisfied demand, while the least exposed ones are located in the centre of the region, away from the boundaries. The municipalities facing the mountains are the most exposed, however. In Dorotea and Sorsele over 80 per cent of the trips will not reach their destinations if a certain link in the respective municipality is closed (Table 2).

Rank	Municipality	Time increase (min/veh)	Characteristics of worst-case link		
			Length (km)	Traffic (veh/day)	Parish, municipality
1	Arjeplog	84	15.6	231	Arjeplog, Arjeplog
2	Jokkmokk	75	1.6	455	Jokkmokk, Jokkmokk
3	Sorsele	69	2.5	375	Sorsele, Sorsele
4	Övertorneå	45	2.0	511	Övertorneå, Övertorneå
5	Storuman	43	0.7	919	Stensele, Storuman

*Table 1: Demand-weighted exposure. The five most exposed municipalities under the worst-case scenario.*

Rank	Municipality	Relative unsatisfied demand	Characteristics of worst-case link		
			Length (km)	Traffic (veh/day)	Parish, municipality
1	Dorotea	0.83	0.1	488	Dorotea, Dorotea
2	Sorsele	0.81	0.3	380	Sorsele, Sorsele
3	Jokkmokk	0.62	4.7	424	Jokkmokk, Jokkmokk
4	Storuman	0.59	0.7	1145	Stensele, Storuman
5	Älvsbyn	0.56	0.3	2393	Älvsby, Älvsbyn

*Table 2: Unsatisfied demand exposure. The five most exposed municipalities under the worst-case scenario.*

## 5. Conclusions

Network vulnerability, or the lack of reliability, is an additional cost for the users: individuals, companies and the society as a whole. Therefore, vulnerability and reliability issues should be included in the assessment of road projects. Road administrations use cost-benefit-analysis for the assessment of different alternatives in road planning. Our measures could be included in such cost-benefit-analyses for comparisons between different alternatives at all levels of the planning process: in the investment stage, in the maintenance stage, as well as in the operational stage. The links that disrupt the network completely should be considered most carefully (the measure of relative unsatisfied demand). Questions that need attention are what real alternatives there are for those people to get to work, or in the case of an emergency situation, how rescue and repair vehicles can get through, evacuation be carried out, etc.

Partly for economic reasons, the focus now is on how the road network performs under normal circumstances. Hazardous events that cause road closures will however inevitably occur, and considering the interdependence between the road infrastructure and other critical infrastructure systems such as electric power and telecommunication, the consequences can be great. Identifying and augmenting critical links can help reduce these consequences.

## 6. Further research

There are a number of possible topics for further work in this area. These include:

- Integrate the calculations with a GIS. This would allow a user to interactively study the importance of a link or the exposure of a node, municipality etc. Calculating the measures on demand, however, requires a highly efficient travel cost algorithm.
- Incorporate more realistic traffic behaviour. However, this would probably also increase the time consumption of the calculations significantly.
- Study how to best reduce exposure and importance by adding new links.
- Develop scenarios and the probability part of vulnerability and criticality.

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