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# **The impact of network density, travel and location patterns on regional road network vulnerability**

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## **Abstract**

We study the influence of the regional location and travel patterns and development of the road network, in terms of its density, on how individuals are affected by disruptions in the network. An extensive vulnerability analysis is carried out in a case study on the Swedish road network. 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. Conclusions for transport planning are discussed.

## **1. Introduction**

Accessibility, the ability to reach attractive locations and activities, is known to affect people's residential as well as mobility choices. Thus, attractive destinations generate travel demand and, given that people's time and money are limited, make it desirable to live close to them (considering both time and cost). Competition on the land and housing markets, however, leads to a trade-off between accessibility and housing costs. As people (and companies, services etc. representing travel destinations) make these choices, spatial location and travel patterns emerge.

The road network constitutes perhaps the most important infrastructure for personal transportation. A more developed road network facilitates shorter travel times to more destinations, increasing accessibility in the region. However, building roads is costly, and the largest benefits of new investments are usually found in regions where the concentration of people is already high. This means that planning authorities face a trade-off between economic efficiency and regional equity and development when allocating resources. The long-term relation between supply and demand is thus one that works in both directions.

This paper considers the influence of the supply-side and demand-side factors mentioned above—regional location and travel patterns and development of the road network (in terms of its density)—on how individuals are affected by disruptions in the network. Disruptions can be caused by a variety of events, some of which originate within the transport system, including traffic accidents and technical failures. Other events are external strains imposed on the system, often caused by nature, as with floods, landslides, heavy snowfall, storms,

wildfires, earthquakes etc. Disruptions caused by nature may extend across large areas in the road network.

Severe network disruptions can threaten the possibility for people to receive medical care and other critical services. More generally, they impair people's accessibility to daily activities such as commuting to work, doing the shopping, etc. It is thus of interest to study the magnitude and distribution of impacts due to disruptions in different parts of the network, so that resources for prevention, mitigation and restoration can be suitably allocated. Knowing the factors underlying the vulnerability helps generalizing the findings to other countries and networks.

The present analysis builds on a series of studies of the Swedish road transport system from which results have been presented in Jenelius (2009, 2010) and Jenelius and Mattsson (2010). We refer to these works for a review of related research in the field. Here we synthesize, complement and expand upon the previously reported findings. 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.

The remainder of the paper is organized as follows. In Section 2 we briefly introduce the Swedish road network, the data, models and procedures used to perform the regional vulnerability calculations. In Section 3 we present the studied vulnerability metrics and findings from the case study, followed by some concluding remarks in Section 4.

## **2. Models, calculations and data**

### *2.1 Impact model*

In this paper we analyze the impacts of road network disruptions, i.e., complete closures of one or several links in the network, for the transport users. We operationalize the impacts as the delays that are caused by the closure as travellers must switch to longer routes or postpone their journeys until the closure has been lifted. We thus study the impacts for individuals' actual travel rather than for their overall accessibility to potential activities and destinations (compare, e.g., Chen et al., 2007 and Taylor, 2008).

To calculate the delays we use the simple model described in detail in Jenelius (2010) and used in Jenelius (2009). The model assumes that travellers' route and departure time choices, but not destination or mode choices, may be affected by link closures. While empirical evidence suggests that this is often a reasonable approximation (see, e.g., Zhu et al., 2009 and references therein), it should be noted that real-world feasible adjustments may be much more complex and may vary depending on where the closure occurs.

We further assume that link travel times are independent of link flows and that all travellers between origin  $i$  and destination  $j$  use the shortest available route, assumed to be unique, from  $i$  to  $j$ . This is a sufficient assumption for most of the studied network where traffic is sparse, but it likely underestimates congestion and travel time changes in and around the major towns and highways. Even in densely populated areas, however, the congestion effects of area-covering disruptions may be smaller than one would initially expect, since users who are unable to travel during the closure will not contribute to congestion.

The delay for a single traveller caused by a closure of any *element*, i.e., single link or collection of links, is then the difference in travel times on the shortest route from  $i$  to  $j$  with and without all links in  $e$  being closed. However, if it is more worthwhile to postpone the trip until the links are reopened, travellers will do so. This aspect of the model becomes effective in places where the road network is very sparse and it is unrealistic to assume that people embark on long detours rather than wait for the closure to be lifted. If the road network is dense, the adjustment becomes insignificant.

Formally, let  $\Delta T_{ij}^e(\tau)$  be the total delay for all users travelling from  $i$  to  $j$  during a closure of all links in element  $e$  with duration  $\tau$ . Let  $x_{ij}$  denote the average travel demand (in vehicles per unit time) between  $i$  and  $j$  during the closure, and let  $\Delta t_{ij}^e$  denote the difference in travel time between the new and the original shortest route, which we assume is known to the users. Further assuming that the travel demand is constant over time, it can be shown (see Jenelius 2010) that the total delay during the closure is

$$\Delta T_{ij}^e(\tau) = \begin{cases} x_{ij} \Delta t_{ij}^e \left( \tau - \frac{\Delta t_{ij}^e}{2} \right) & \text{if } \Delta t_{ij}^e < \tau, \\ \frac{x_{ij} \tau^2}{2} & \text{if } \tau \leq \Delta t_{ij}^e < \infty. \end{cases} \quad (1)$$

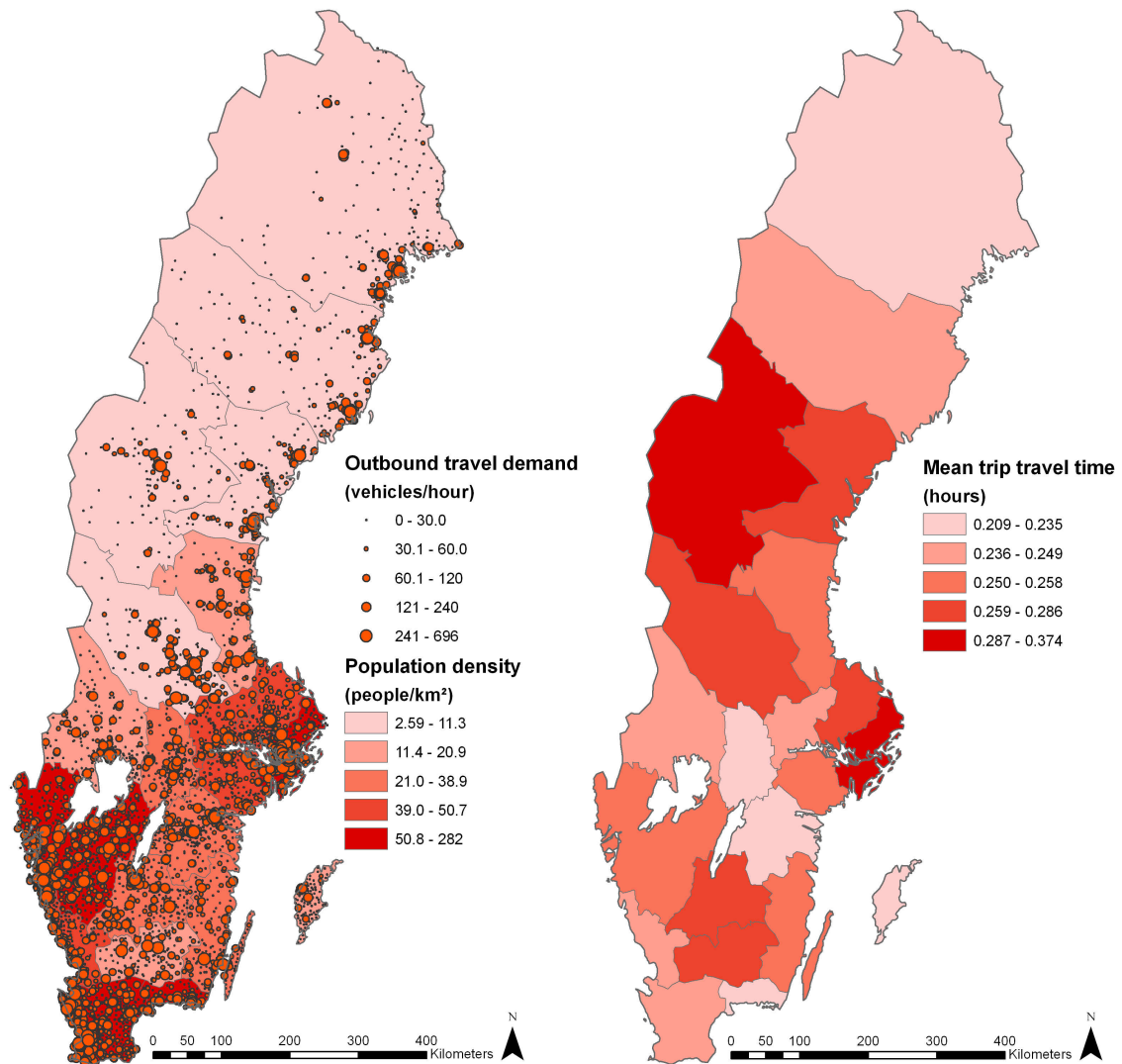
If there are no alternative routes (which can be expressed as  $\Delta t_{ij}^e = \infty$ ), the best a user can do is to wait until the closure is lifted. A user wishing to depart during the closure will on average be delayed  $\tau / 2$  time units. The total travel demand during the closure is  $x_{ij} \tau$  and the total delay during this period is

$$\Delta T_{ij}^e(\tau) = \frac{x_{ij} \tau^2}{2} \quad \text{if } \Delta t_{ij}^e = \infty. \quad (2)$$

Following Jenelius et al. (2006), we refer to the users who are unable to travel (excluding those who voluntarily postpone their trips) during the closure as *unsatisfied demand*. Elements that when closed cause unsatisfied demand are called cut elements; in particular, single links with this property are called cut links. Note that  $\tau$  can be seen as a weight parameter controlling the relative impact of not being able to travel versus travelling but incurring delays.

## 2.2 Data and calculations

The network and travel demand data (including both car and truck trips) used for the analysis were obtained from the Swedish national travel demand model system SAMPERS (Beser and Algiers, 2001). For more information about this source of data, see Jenelius et al. (2006), Jenelius and Mattsson (2010). After some pre-processing the road network model consists of 32759 nodes (including 8764 origin/destination, OD, nodes) and 86940 directed links, representing a very fine level of detail. A few links in Norway and Finland have been added to provide alternative routes and reduce border effects, but are not closed in the vulnerability analysis; neither are the ferry links to the island of Gotland. Throughout the case study we have assumed that the duration of the closures is 12 hours.



**Figure 1: Characteristics of the study area, Sweden. Left: Population density of counties (people/km<sup>2</sup>), outbound travel demand of origin/destination nodes (vehicles/hour). Right: Mean trip travel time of counties (hours).**

In order to study the impacts of area-covering disruptions we make a complete coverage of the study area using evenly displaced grids of uniformly shaped and sized *cells*. In this approach, described in more detail in Jenelius and Mattsson (2010), each cell represents the precise spatial location and extent of a disrupting event. To simulate the event, any road links intersecting the cell (fully or partially) are completely closed for the duration of the disruption, while all links outside the cell are completely unaffected. In this study we have used square cells to represent the disrupting events and will focus on results obtained using grids of  $12.5 \times 12.5$  km<sup>2</sup> cells. For increased precision we have used four grids, symmetrically displaced in two longitudinal and two latitudinal steps, so that four different cells cover every point in the study area.

For the area-covering disruptions the analysis procedure relies heavily on GIS techniques. GIS software (ArcGIS 9.2) was used to create the grids, to identify all cells intersecting the study area and to identify all links and origins/destinations intersecting each cell (see further Jenelius and Mattsson 2010). These data were imported into specially developed software written in C++/C#, where the impact calculations were performed. The results were then returned to the GIS for visualization.

### 2.3 Characteristics of the study area

Figure 1 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. Jenelius (2009) 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 2 below.

## 3. Vulnerability and its determinants

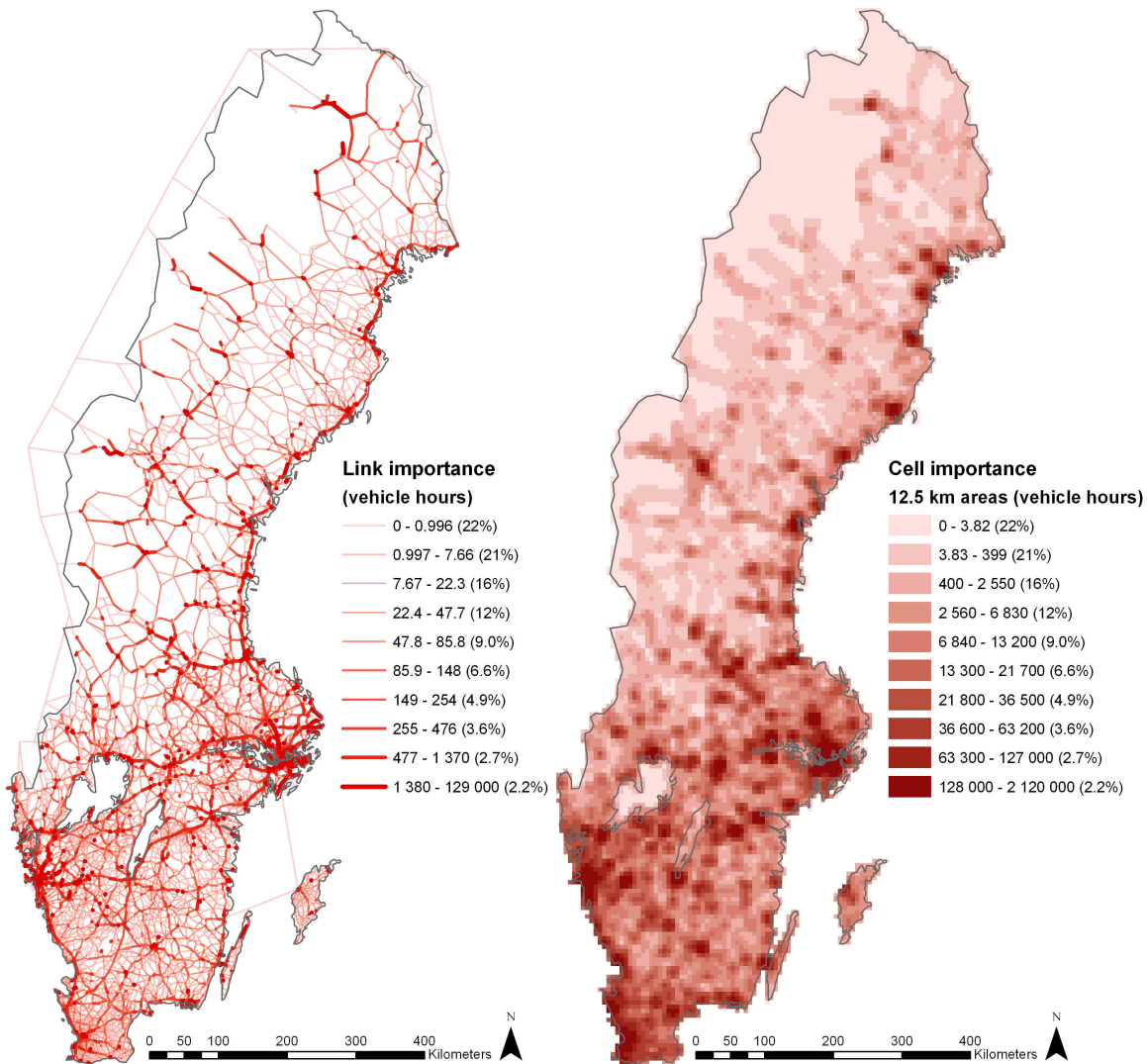
### 3.1 Link and cell importance

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 total impact of a closure is referred to as the *importance* of the element  $e$  and, given closure duration  $\tau$ , can be written as

$$I(e | \tau) = \sum_i \sum_j \Delta T_{ij}^e(\tau). \quad (3)$$

When the element is a single link, it is fairly straightforward to see the determinants of its importance. As noted by for example Jenelius (2009, 2010), 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. The longer the closure duration  $\tau$ , 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. Closing all links within a cell 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 outbound trips will dominate over through-going 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 by Jenelius and Mattsson (2010), 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-going trips incurring delays.



**Figure 2: Element importance, 12 hour closure duration. Left: Single links. Right: 12.5 km cells.**

Figure 2 shows the importance of every link in the Swedish road network model to the left and every 12.5 km cell in the grids covering the study area to the right, assuming a 12-hour closure. 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 1. This confirms the general observation that the impacts of area-covering disruptions are most severe in areas 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.

### 3.2 Worst-case user exposure

Our second perspective of vulnerability focuses on the impacts for individual users under different disruption scenarios. The mean impact for a user in a given region (e.g., a municipality or county) of the study area under a specific scenario is termed the *user exposure* of the region relative to the scenario. Formally, we let a basic scenario consist of an element (a link or group of links)  $e$  that is closed for a duration  $\tau$ . We let  $r$  denote a region in the study area and let  $i \in r$  mean that origin  $i$  is located within region  $r$ . The user exposure of region  $r$  relative to scenario  $(e, \tau)$  can then be written as

$$UE(r | e, \tau) = \frac{\sum_{i \in r} \sum_j \Delta T_{ij}^e(\tau)}{\sum_{i \in r} \sum_j x_{ij} \tau} \quad (4)$$

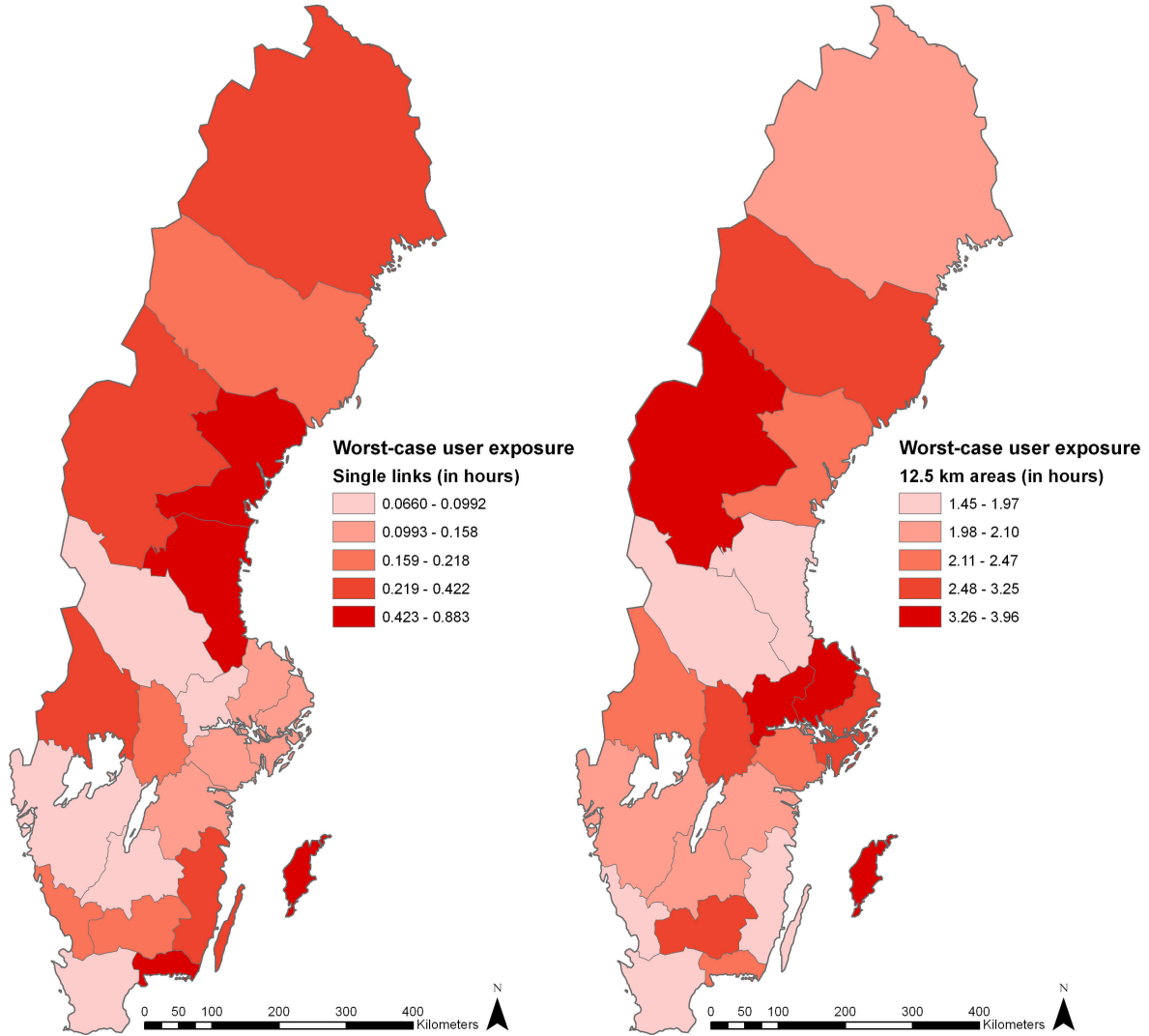
We will here consider two specific kinds of scenarios. The first is a *worst-case* scenario for the region, i.e., the element  $e$  causing the largest impact for the region given the closure duration (among some prior collection of considered potential elements) is closed. The worst-case user exposure of region  $r$  is thus

$$UE_{wc}(r | \tau) = \max_e \frac{\sum_{i \in r} \sum_j \Delta T_{ij}^e(\tau)}{\sum_{i \in r} \sum_j x_{ij} \tau}. \quad (5)$$

When the elements are single links, the worst-case user exposure represents the largest possible impact of a single link closure on the users travelling within and out from a specific 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. Jenelius (2009) found 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 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. Jenelius and Mattsson (2010) found 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 region's total 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 or end will be particularly exposed to this kind of scenario. At the opposite end are regions with highly dispersed location and travel patterns.





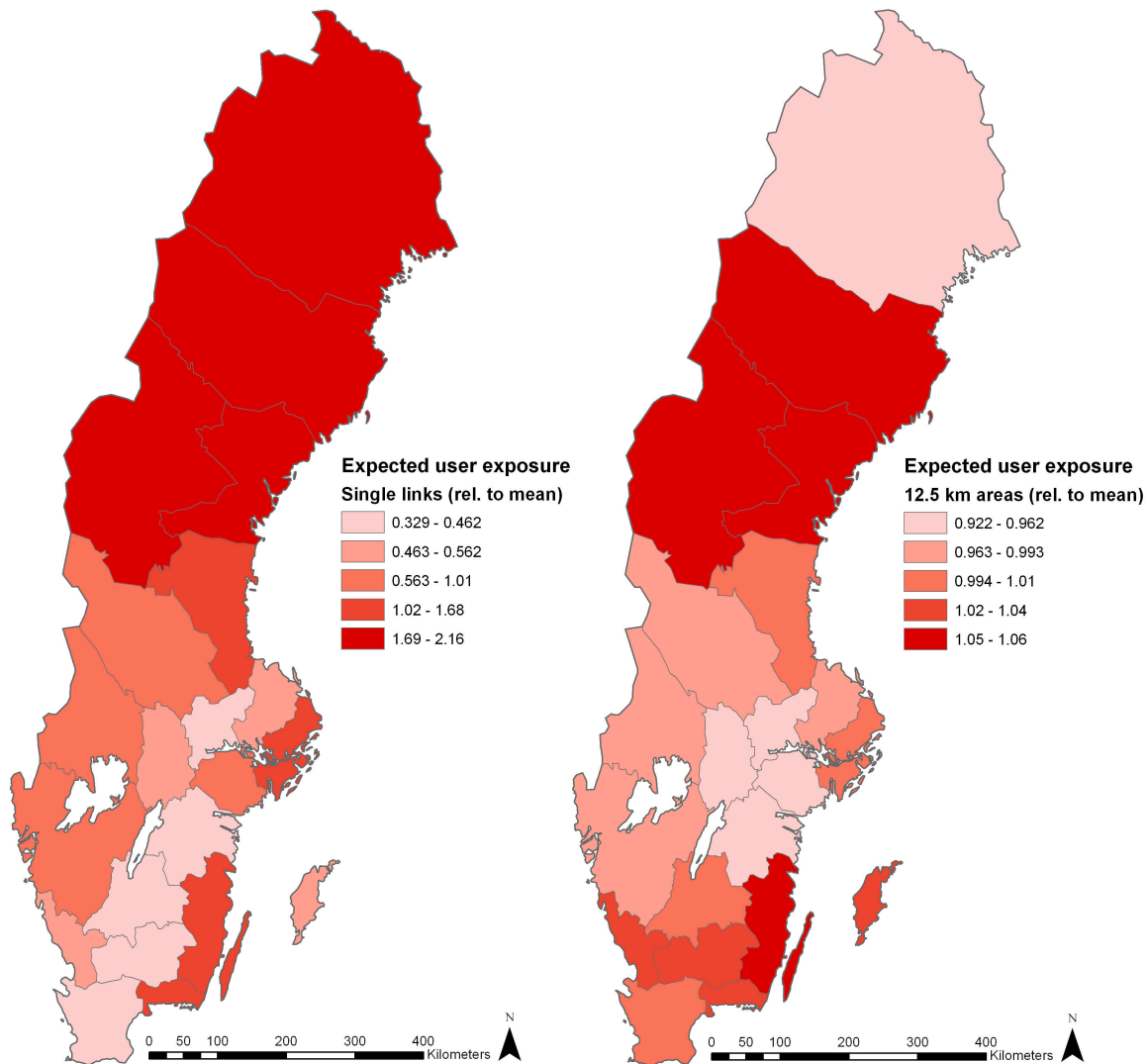
**Figure 3: Worst-case user exposure of Swedish counties, 12 hour closure duration. Left: Single link closures. Right: 12.5 km cell closures.**

Figure 3 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 show quite few similarities with each other. This is not unexpected since the worst-case exposure to single link closures is highly 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.

### 3.2 Expected user exposure

The second type of exposure that we consider is the *expected* (or average-case) impacts for the region under all possible scenarios. With  $p_e$  denoting the probability that element  $e$  is closed for a specific duration  $\tau$ , the expected user exposure of region  $r$  is

$$UE_{\text{exp}}(r | \tau) = \sum_e p_e \frac{\sum_{i \in r} \sum_j \Delta T_{ij}^e(\tau)}{\sum_{i \in r} \sum_j x_{ij} \tau}. \quad (6)$$



**Figure 4: Expected user exposure of Swedish counties, 12 hour closure duration. Left: Single link closures. Right: 12.5 km cell closures.**

For single link closures we assume here that the closure probability is proportional to the length of the link (note that only relative probabilities are necessary for relative rankings of different regions). This means that every road segment of unit length has the same probability of being closed and represents a first approximation of the probability that some external event disrupts each link. For cell closures 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 by Jenelius (2009), the expected user exposure of a region to single link failures is large if the trips are long on average, so that the users run a large risk 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 disrupt large shares of the trips or whether many cells disrupt small shares 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-going 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 4 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.

#### **4. Conclusions**

We have studied the determinants behind regional variations in vulnerability and have found significant influences from travel patterns, location patterns and the development of the road network. Our findings, which should be universal for most road networks of similar scale, reveal that the vulnerability to single link failures and spatially spread events are influenced by quite different factors and hence display somewhat different regional distributions. Furthermore, these regional disparities stem from fundamental properties of the transport system and the population distribution. Therefore we believe that resource allocation for reducing vulnerability, for which analyses of this kind is useful, is more an issue of preparedness and mitigation than redundancy-providing infrastructure investments. An exception may be identified worst-case scenarios, for which targeted actions such as redundancy-improving road investments may have considerable positive effects. Of course, the benefits of such investments must be put in relation to their costs.

An interesting question related to the study presented here is whether vulnerability in itself affects people’s location and travel patterns, so that there are influences working in both directions. It is conceivable, for example, that some people choose not to locate in certain areas to avoid the risk of large transport network disruptions. Regarding the supply-side, it would also be interesting to investigate to what extent roads are built and other investments are made (at least partially) in order to reduce the impacts of network disruptions rather than provide more efficient transportation.

In order to allocate resources for reducing vulnerability efficiently, it is valuable to combine the impact calculations with assessments of the frequencies with which different kinds of disruptive events can be expected to occur in different parts of the study area. As for any rare events, estimating these frequencies is a difficult task, and good estimates may depend on

specific environmental features of each area. However, the likelihood of flooding in an area, for example, is certainly influenced by the precipitation, for which detailed historical or modelled future data on both average and extreme levels are often available. Development of the methodology for likelihood assessments in vulnerability analysis should be an important area for further work.

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