

# **GEOGRAPHY AND ROAD NETWORK VULNERABILITY: REGIONAL EQUITY VS. ECONOMIC EFFICIENCY**

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## **Abstract**

We investigate the significance of geography for road network vulnerability. By our definitions, a region is exposed if the consequences of a random road closure are severe for this region, and it is important if the consequences of a road closure within the region are severe for the overall network traffic. In a case study of the Swedish road network we study the distribution of exposure and importance among municipalities and counties. We find considerable regional inequity of exposure, in particular for long closure durations. We also identify network regions that are particularly important for the socio-economic efficiency of the road transport system. Furthermore, we have developed simple proxy variables that can be used as rough estimates of exposure and importance and provide a better understanding of the factors underlying these measures. The policy implications of the findings are discussed.

## **1. Introduction**

Issues of transport reliability and road network vulnerability are now receiving increasing and much needed attention. There is a growing awareness of the need to study the performance of the transport system under different kinds of disturbances (e.g., Nicholson & Du, 1997; Berdica, 2002; Ham et al., 2005). Methods to measure and assess the consequences of link closures have been and continue to be developed (e.g., Jenelius et al., 2006; Taylor et al., 2006). We believe that it is now time to go deeper into the vulnerability analysis.

In this paper, we investigate the geographic significance for road network vulnerability. The idea is to develop a method that can be generally applied to almost any road network in the world. Then, similarities and differences between different countries and regions could be identified and discussed. The method can also be used as a guide for policy decisions such as the prioritization among different road projects and investments for renewal, maintenance and operation.

An important issue in transport policy is the trade-off between maximising the socio-economic efficiency and developing regional equity. This is not least valid in connection with vulnerability. The consequences of closing a link in a dense region with a heavily used road network may seem obviously worse than in a region where the network is sparse and scarcely used. However, the former case may only cause short delays for each individual user, while the latter case may lead to very long delays. We will consider both sides of this coin.

From the users' point of view, we say that a region is particularly *exposed* if the consequences of a disruption somewhere in the road network are particularly severe for the users in this region. From the network's point of view, we say that a region is particularly *important* if the consequences of a disruption somewhere in this region are particularly severe for the overall network traffic. In a case study of the Swedish road network, we will investigate the regional variations in these measures. Large differences in exposure between regions are an indicator of regional inequity in the road transport system, while large differences in importance between regions indicate that the network is inefficient under disruptions. We will also study whether some fundamental properties of the geography, the network and the traffic can help explain the differences in exposure and importance between different regions. Such a finding would allow us to get a rough estimate of the exposure and importance of a region without the need for extensive calculations or much data. It would also provide valuable insights into what reinforcements of the road network can help reduce the exposure or importance of a region.

## 2. Measuring the consequences of a closure

The event that will be studied throughout this paper is a complete closure of a single road link. The consequences of such a link closure are measured here as the increase in travel time, or rather the delayed arrival, that follows from the closure. The important factors that determine the magnitude of the consequences are:

- duration of the closure,
- OD demand flows,
- existence of alternative routes, and if so,
- travel times on the alternative routes.

We use a simple and conservative way to model the effects of a closure. Consider a single origin  $o$  and destination  $d$  and assume that the travel demand from  $o$  to  $d$  is  $x_{od}$  vehicles per unit time, constant and inelastic. Assume also that there is initially at least one route between  $o$  and  $d$ , that the travel time is independent of the traffic volume and that all users choose to travel along the shortest route.

Suppose now that link  $k$  is located along the shortest route from  $o$  to  $d$ . At  $t = 0$  this link is closed for all traffic and at  $t = t_{\text{open}}$  it is reopened. To keep things simple, we assume that the users immediately know the duration of the closure. During the closure, there may be either no or at least one alternative route from  $o$  to  $d$ . We will now consider these two cases in turn.

### 2.1. No alternative routes

If there are no alternative routes during the closure, the best a user can do is to wait until link  $k$  is reopened. Henceforth, a link of this kind will be called a *cut link*. Since the travel demand is constant over time, a user wishing to depart during the closure will on average be delayed  $t_{\text{open}}/2$  time units. The total demand during the closure is  $x_{od}t_{\text{open}}$  and the increase in total travel time during this period is

$$\Delta T_{od}^k = \frac{x_{od}t_{\text{open}}^2}{2} \quad \text{if } k \text{ is a cut link.} \quad (1)$$

## 2.2. Alternative routes

If there are alternative routes, a user can choose to travel along the new shortest route or to wait until link  $k$  is reopened. Let  $\Delta\tau_{od}^k$  denote the difference in travel time between the new and the original shortest route, which we assume is known to the users. The delay for a user wishing to depart at time  $t \in [0, t_{\text{open}})$  will be  $\min(\Delta\tau_{od}^k, t_{\text{open}} - t)$ . If  $\Delta\tau_{od}^k \geq t_{\text{open}}$ , all users wishing to depart during the closure will delay their trips, which gives the same result as if there were no alternative routes. If  $\Delta\tau_{od}^k < t_{\text{open}}$ , only the users wishing to depart after  $t = t_{\text{open}} - \Delta\tau_{od}^k$  will benefit from delaying their trip instead of taking the detour. It is straightforward to show that the increase in total travel time in any case is

$$\Delta T_{od}^k = \begin{cases} \frac{x_{od} t_{\text{open}}^2}{2} & \text{if } \Delta\tau_{od}^k \geq t_{\text{open}}, \\ x_{od} \Delta\tau_{od}^k \left( t_{\text{open}} - \frac{\Delta\tau_{od}^k}{2} \right) & \text{if } \Delta\tau_{od}^k < t_{\text{open}}. \end{cases} \quad (2)$$

## 3. Measures of regional exposure and importance

### 3.1. Regional exposure

The exposure of a region to a certain scenario was defined in Jenelius et al. (2006) as the magnitude of the consequences for the region if the scenario were to occur. Here we consider a simple average-case scenario in which we calculate the expected effects of a closure somewhere in the network, where the probability of closure per unit road length is constant. This should be a reasonable first approximation of the “true” closure probabilities, and within our setting, it is equivalent to closing a randomly chosen link with probabilities proportional to the lengths of the links.

Two measures of regional exposure are used here:

- *User exposure*: the average increase in travel time per trip starting within the region during the closure.
- *Total exposure*: the total increase in vehicle travel time for all trips starting within the region during the closure.

Let  $r$  denote a region, let  $l_k$  be the length of link  $k$  and let  $w_k = l_k / \sum_{\kappa} l_{\kappa}$  be the closure probability of link  $k$ . Then the user exposure  $UE$  of region  $r$  is

$$UE(r) = \frac{\sum_k w_k \sum_{o \in r} \sum_{d \neq o} \Delta T_{od}^k}{\sum_{o \in r} \sum_{d \neq o} x_{od} t_{\text{open}}}, \quad (3)$$

and the total exposure  $TE$  of region  $r$  is

$$TE(r) = \sum_k w_k \sum_{o \in r} \sum_{d \neq o} \Delta T_{od}^k. \quad (4)$$

A road transport system would be perfectly equitable in terms of user exposure if the expected consequences for a user would be the same regardless of what region the trip was

undertaken from. For a geographically disparate transport system, this will generally not be the case. Instead, users in regions with less extended transport infrastructure are likely to suffer more from a disrupting event.

Total exposure, on the other hand, represents the expected socio-economic costs for the region, since travel time changes are generally the dominating component in socio-economic valuations. To translate the travel times into monetary units, some appropriate value-of-time factor should be used. A road transport system would be perfectly equitable in terms of total exposure if the expected socio-economic costs of a closure would be the same for all regions. Again, this will most likely not be the case in reality.

By studying the regional distribution of the user and total exposure for a particular road transport system, we can evaluate the regional inequity with respect to these measures. A common measure of inequity and inequality is the Gini coefficient  $G$ . The values of  $G$  can range from 0 to 1, where 0 indicates perfect equity and 1 indicates perfect inequity.

### 3.2. Regional importance

The importance of a link was defined in Jenelius et al. (2006) as the magnitude of the consequences for all users should the link be closed. As a measure of the importance of a region we calculate the expected effects for all users of a closure somewhere in the region, where the probability of closure per unit road length is constant. Note that there is little point in differentiating between total importance and user importance, since these measures would differ only by the same factor for all links (namely, the total travel demand during the closure). Let  $\omega_k = l_k / \sum_{k \in r} l_k$  be the closure probability of link  $k$  located in region  $r$ .

Then the importance  $I$  of region  $r$  is

$$I(r) = \sum_{k \in r} \omega_k \sum_o \sum_{d \neq o} \Delta T_{od}^k. \quad (5)$$

The importance of a region expresses how the total socio-economic efficiency of the road transport system is affected by a random closure in the region.

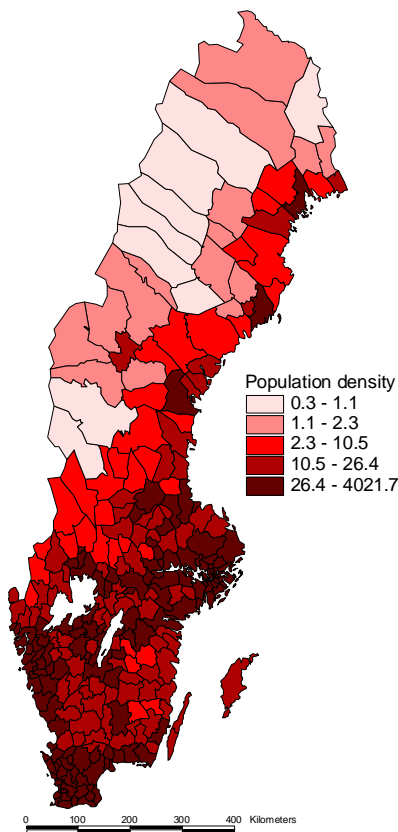
### 3.3. Effects of the closure duration

The duration of the closure will in general affect the relative exposure and importance of different regions. It is clear from (1) and (2) that the benefit from short alternative routes will increase with the closure duration  $t_{\text{open}}$ , since the consequences will then be linear in  $t_{\text{open}}$ , while they will be quadratic in  $t_{\text{open}}$  if there are no short alternative routes. A robust exposure and importance analysis should therefore be based on some typical closure duration, or preferably a range of different durations.

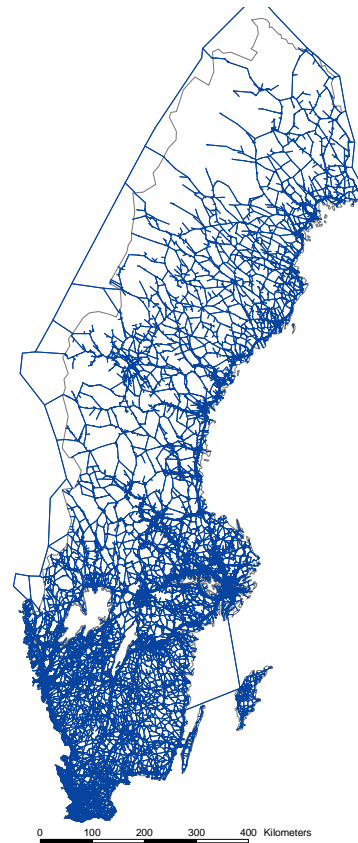
## 4. Case study: The Swedish road network

### 4.1. Geographic context

Sweden was in 2001 divided into 289 municipalities and 21 counties, each county comprising between 1 and 26 municipalities. The population density of the municipalities in 2001 is shown in figure 1 (data from Statistics Sweden). As can be seen, the population is concentrated to the southern parts of the country. A major historical cause for this is the climate, which is gentler and more favourable for agriculture and animal breeding in the



**Figure 1: Population density (km<sup>-2</sup>). Data from Statistics Sweden.**



**Figure 2: The road network**

south. Also, the Fennoscandian mountain chain along the border to Norway in the northwest provides harsh conditions for cultivation. Sweden also borders on Finland in the northeast, while the remaining national border follows the coast of the Baltic sea.

The distribution of the population is reflected in the road network, which is shown in figure 2. Not surprisingly, there is a strong correlation between population density and road density, as measured by the kilometres of road per square kilometres of surface, in the municipalities. A perfect correlation would imply that the kilometres of road per inhabitant of each municipality be constant. However, our analysis shows that the kilometres of road per inhabitant are inversely proportional to the square root of the population density (a linear regression analysis with the square root of the inverse population density as the independent variable gives adj.  $R^2 = 0.89$ ), a relationship that also holds for counties (adj.  $R^2 = 0.85$ ). Thus, sparsely populated regions generally have more kilometres of road per inhabitant than densely populated regions.

#### 4.2. Data

In order to calculate the regional exposure and importance measures, the following data are necessary:

- network representation with nodes, links and centroids,
- length and travel time of every link,
- OD travel demand between every centroid pair,
- appropriate regional coding of every link and centroid.

We have obtained the first three sets of data from the Swedish national travel demand model system SAMPERS (Beser and Algiers, 2001), which utilizes EMME/2 to perform user equilibrium traffic assignments. For local and regional trips, SAMPERS divides Sweden into approximately 8,500 zones where all trips begin and end, each zone comprising approximately 1,000 inhabitants. The centre of gravity of each zone is represented by a centroid.

For computational reasons, the SAMPERS system does not use a representation of the entire Swedish transport system at the fullest detail, but has divided it into five complementary submodels. Each submodel is focused on a specific region where the network and the zones are represented at their fullest detail, while the rest of the country is more coarsely represented. To obtain a fully detailed representation of the entire Swedish road transport system, we have merged the regional submodels into a single national model by “stitching together” the focus regions of the submodels. To preserve the trips across the focus region borders, we have mapped every centroid outside the focus region of its submodel to the geographically closest centroid in the new national model. Using this mapping, the OD travel demand matrices of the submodels have been merged into a single OD travel demand matrix for the national model. The resulting national road network, shown in figure 2, consists of 77,769 nodes, including 8,764 centroids, and 174,044 directed links. The travel time of each link is obtained from user equilibrium assignments in Emme/2 on each regional submodel. The OD travel demand matrix used in this study only includes trips made by car.

In the original network representations in SAMPERS, roads are divided into shorter sections with varying characteristics such as different volume-delay functions. With our model a closure of any of these links would have the same consequences, but how these more or less arbitrary divisions are made affects the topological network measures introduced below. Therefore, we have replaced links connected in series with a single link and kept only the nodes that mark the dead ends of roads or where more than two road sections join. This gives a unique, and in a sense the most fundamental, representation of the network.

To obtain the municipality and county in which every node and link is located, we have imported the node coordinates into a GIS and projected them onto municipality and county maps. The links are defined to be located in the municipality in which their tail node is located.

#### *4.3. Case study specifications*

We have studied two different closure durations:

- a short closure of 30 minutes,
- a long closure of 48 hours.

For both closure durations we have calculated the regional exposure and importance of every municipality and county in Sweden. First, we have analyzed the spatial patterns of these measures in a mainly descriptive way, in particular regarding the regional equity and socio-economic efficiency of the road transport system. Second, we have looked for regional properties of the road network, the traffic and the geography that can help explain

the observed regional differences in the exposure and importance measures, and also be able to serve as proxy variables for these measures.

As it turned out, attempts to find proxies for regional exposure and importance were much more successful for the short closure than for the long closure. This was not unexpected, since cut links have much greater impact on the average consequences of the long closure than of the short closure. The distribution of cut links in the network, in turn, is quite random and has little connection with the properties of the surrounding network such as the road density. It is therefore unlikely that there exists any reliable proxy for the expected consequences of a long closure that does not explicitly involve considering and identifying the cut links. In the following, we will focus on the short closure duration, and results for the long closure duration will be limited mainly to the user exposure.

In the consequence model used here it is assumed that the closure of a link does not affect the travel time of any other link. Without this simplification, the calculations could not have been completed in reasonable time. The approximation should be valid for most of the Swedish road network, which is largely uncongested. In densely populated areas, however, the model likely underestimates the true consequences of a closure. This should be kept in mind when evaluating the results below.

#### *4.4. Distributions of regional exposure and importance*

##### *4.4.1. Distribution of regional user exposure*

Figure 3 shows the user exposure of each municipality to the 30 minutes closure scenario (“short user exposure” for short). There is a clear geographic pattern in the distribution in that the southern parts of Sweden are considerably less exposed than the northern parts. In particular, many of the most exposed municipalities are located in the mountainous areas in the northwest, where both the population and the road network are very sparse, as figures 1 and 2 show. Thus, a person travelling by car from a northwestern municipality should expect considerably longer delays than a person travelling from a southern municipality.

Figure 4 shows the user exposure to the 48 hours closure scenario (“long user exposure” for short). By definition, the longer the closure, the more influence will cut links have on the expected consequences. Thus, municipalities where a large share of the trips normally use cut links will be the most exposed. These municipalities tend to be concentrated mainly along the coasts, where there are more cut links than in the inland regions. The narrow island Öland close to the southeast coast, for example, relies on several cut links including a single bridge connecting it to the mainland. Öland consists of two municipalities, which rank as 64 and 73 for the short closure scenario, but as 5 and 7 for the long closure scenario, respectively.

The Gini coefficient for the short user exposure of the municipalities is  $G = 0.36$ , while for the long user exposure,  $G = 0.65$ . The regional inequity of user exposure is thus considerably larger for a long closure than a short closure.

Comparing figures 1 and 3 suggests that the exposure is high where the population density is low and vice versa. In fact, there is a clear linear relationship between the user exposure and the *square root* of the inverse population density (a regression analysis with the latter quantity as the independent variable gives adj.  $R^2 = 0.75$ ). The reason for the square root improving the fit seems to be the nonlinearities that are introduced through the possibility

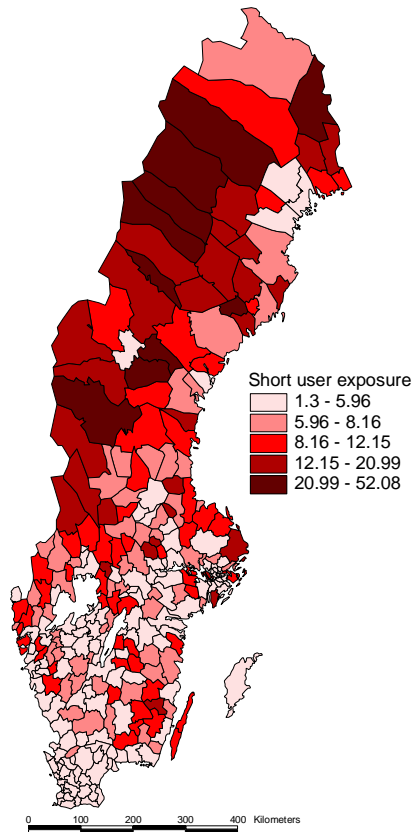


Figure 3: Short user exposure ( $10^{-6}$  hours)

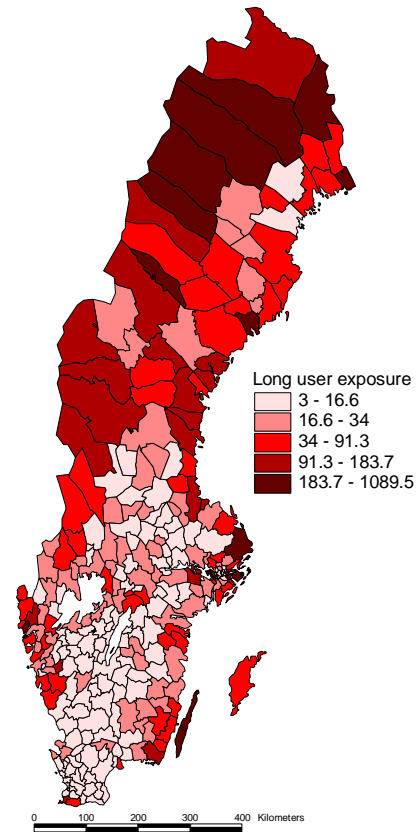


Figure 4: Long user exposure ( $10^{-6}$  hours)

for the users to delay their trip if a detour would be longer. This puts a cap on the consequences that becomes more restrictive the longer the detours. Calculations show that if the delay choice is prohibited, there is indeed a more direct linear relationship between the inverse population density and the short user exposure.

#### 4.4.2. Distribution of regional total exposure

Figure 5 shows the total exposure of each municipality to the 30 minutes closure scenario (“short total exposure” for short). The geographic pattern follows the population quite well, which makes sense since the total travel demand is roughly proportional to the population. The most exposed municipality is Stockholm, followed by other main population centres. Relative to their populations, Malmö and other southern municipalities are fairly unexposed, and the northwestern municipalities are well off since very little traffic is generated there.

The Gini coefficient for the short total exposure is  $G = 0.43$ , slightly larger than for the short user exposure, and again it is much larger for the long closure exposure,  $G = 0.71$ . These values suggest that the regional inequity of total exposure is similar to but slightly higher than that of user exposure.

#### 4.4.3. Distribution of regional importance

Figure 6 shows the importance of each municipality for the 30 minutes closure (“short importance” for short). The geographic pattern is fairly similar to that of the short total exposure in figure 5, with some variations. The difference between exposure and importance is, simply put, that exposure expresses how dependent the region is on the whole road transport system, while importance expresses how dependent the road transport system is on the region. By definition, the importance will be relatively higher than the

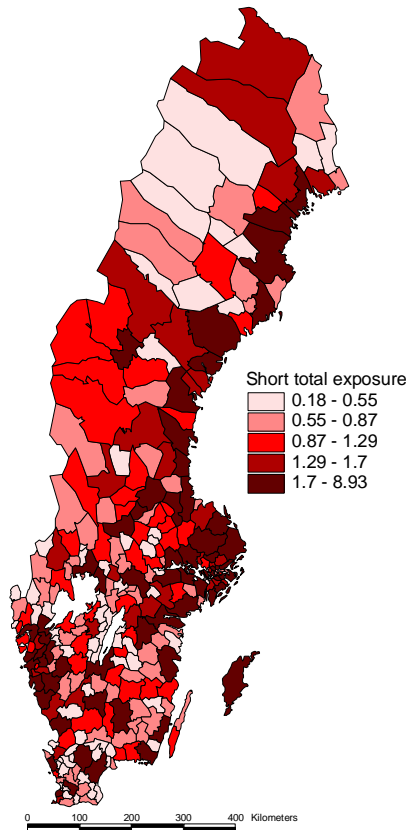


Figure 5: Short total exposure ( $10^{-3}$  hours)

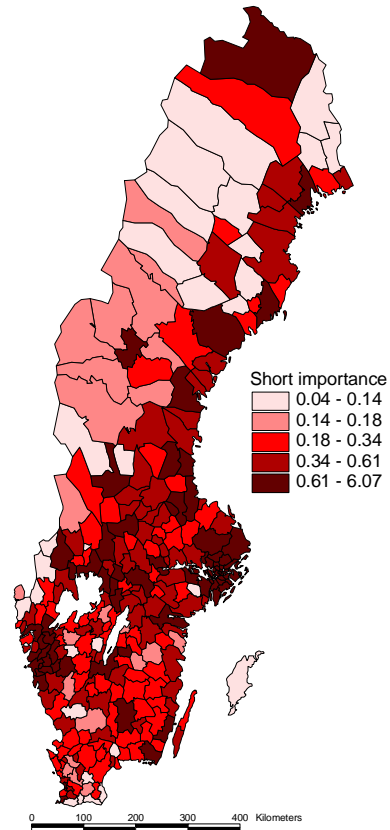


Figure 6: Short importance (hours)

total exposure if there is much externally generated traffic passing through the region, if the internally generated traffic is largely contained within the region, or if the total road length in the region is comparatively short. This can be seen by separating (4) into two parts based on whether the link is located within the region or not, and separating (5) in the same way based on the location of the start centroids.

Many of the most important municipalities are located around Stockholm, particularly along the coast, while Stockholm itself ranks only as 25. This is because much traffic is generated in and passes through these regions, while the networks there are quite tree-like and contain many cut links. Many municipalities in southern Sweden are also ranked higher in terms of importance than of total exposure because of the busy traffic between the three main population centres, Stockholm, Gothenburg and Malmö.

The Gini coefficient provides useful information about the distribution of the regional importance, although it may be misleading to talk of it in terms of inequity. The Gini coefficient for the short importance is  $G = 0.52$ , while for the long closure importance,  $G = 0.86$ . This shows that the socio-economic efficiency of the road transport system is highly dependent on the road networks in a small number of municipalities, in particular those around Stockholm mentioned above, and increasingly so for longer closures.

#### 4.5. Proxies for regional exposure and importance

The process of calculating the exposure and importance of every region in a large road transport system is time consuming and requires much data that may be difficult to acquire, such as the travel time of every link. An important question is whether there are some

alternative and simpler variables that can serve as first approximations of these measures. For the Swedish road transport system we have found that in many cases there is.

#### 4.5.1. Proxies for short user exposure

Intuitively, the user exposure of a region is mainly influenced by two factors: the sparsity of the road network and the initial travel patterns of the users in the region. Since most trips are local, the local properties of the road network should have a large impact on the exposure, even though we calculate the average consequences over all links.

There are several possible measures of road network sparsity, and its inverse, road network density. The perhaps most common geographic measure of road density is the total length of the road network in the region,  $L_r$ , divided by the size of the region,  $A_r$ . A measure of geographic road sparsity would thus be the inverse of this,  $A_r/L_r$ . In this study, we have in fact found that a better measure for our purposes is

$$GS_r = \sqrt{\frac{A_r}{L_r}}, \quad (6)$$

where  $GS$  stands for “geographic sparsity”. The square root is entirely experimental and we presently lack a theoretical motivation for it, though there is a parallel for the inverse population density discussed in sections 4.1 and 4.4.1. The data required to calculate the geographic sparsity should be relatively easy to obtain.

Another approach is to consider the topology of the road network. Intuitively, the longer the links, the longer a detour will be on average. Also, the less links per node, the less likely it is that there exists a short detour. Thus, a measure of the local sparsity of the network is the average link length divided by the links-to-nodes ratio of the region. The links-to-nodes ratio is also known as the  $\beta$ -factor. We get

$$NS_r = \frac{\bar{l}_r}{\beta_r}, \quad (7)$$

where  $NS$  stands for “network sparsity”,  $\bar{l}_r$  is the average edge length, and  $\beta_r$  is the links-to-nodes ratio of region  $r$ , respectively. A network representation of the road system would be necessary to calculate the network sparsity.

The second important factor for the user exposure is the original travel patterns of the users in the region. If the average user travel time before the closure is small, it is likely that the expected increase in user travel time will also be small. The average user travel time of a region may be difficult to obtain without access to some form of transport modelling system, but one way may be through travel surveys.

A proxy variable for the short user exposure of a region is obtained by multiplying one of the road network sparsity measures with the average user travel time  $\tau_r$ . Using the geographic sparsity  $GS$  we get a proxy variable  $GPSUE$  (“Geographic sparsity Proxy for Short User Exposure”), and using the network sparsity  $NS$  we get a proxy variable  $NPSUE$  (“Network sparsity Proxy for Short User Exposure”). Formally,

$$GPSUE(r) = GS_r \cdot \tau_r = \sqrt{\frac{A_r}{L_r}} \cdot \tau_r, \quad (8)$$

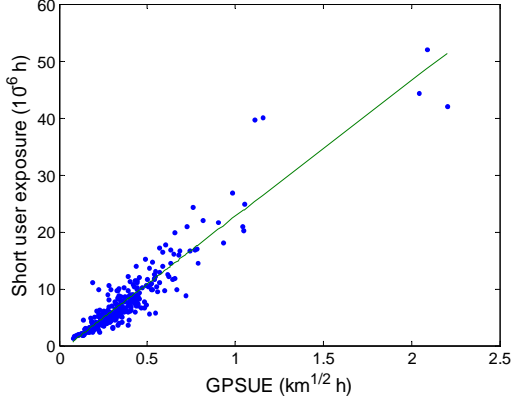


Figure 7: Fitted regression line for GPSUE vs. short user exposure

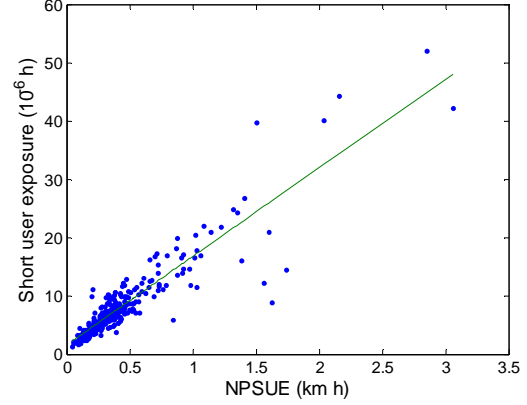


Figure 8: Fitted regression line for NPSUE vs. short user exposure

$$NPSUE(r) = NS_r \cdot \tau_r = \frac{\bar{l}_r \cdot \tau_r}{\beta_r}. \quad (9)$$

We have performed two linear regression analyses of the Swedish municipalities using *GPSUE* and *NPSUE*, respectively, as the independent variable and the short user exposure as the dependent variable. The results are shown in figures 7 and 8; parameter values are given in the appendix. The explanatory powers of the two proxy variables are similar, with *GPSUE* performing slightly better (adj.  $R^2 = 0.87$  for *GPSUE*, adj.  $R^2 = 0.83$  for *NPSUE*). The residuals from either regression analysis display no obvious spatial autocorrelation, although they are generally larger in magnitude for the northern municipalities. This makes sense since sparse regions should be more sensitive to small variations in the network configuration.

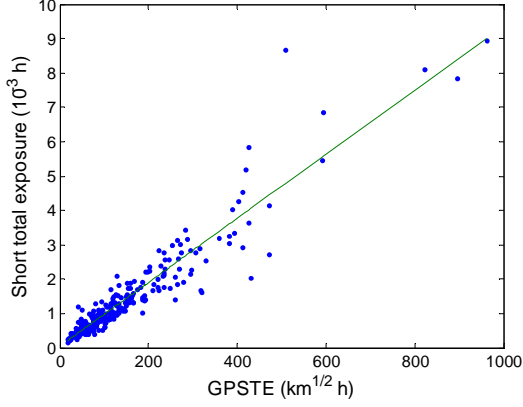
#### 4.5.2. Proxies for short total exposure

In the same way as for the short user exposure, we can construct proxy variables for short total exposure based on the local density of the road network and the travel patterns of the users. Rather than the average user travel time, however, it is reasonable that the total exposure is proportional to the total user travel time  $T_r$ . Using the geographic sparsity  $GS$  we get a proxy variable *GPSTE* (“Geographic sparsity Proxy for Short Total Exposure”), and using the network sparsity  $NS$  we get a proxy variable *NPSTE* (“Network sparsity Proxy for Short Total Exposure”). Formally,

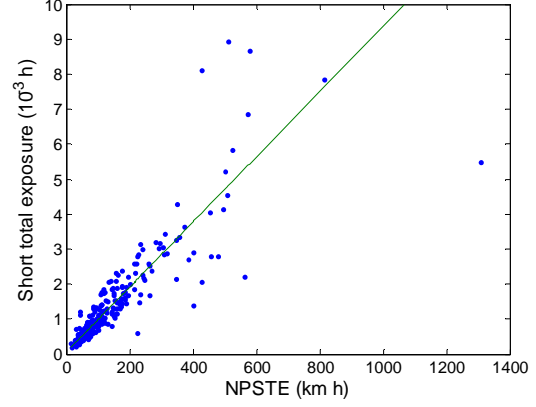
$$GPSTE(r) = GS_r \cdot T_r = \sqrt{\frac{A_r}{L_r}} \cdot T_r, \quad (10)$$

$$NPSTE(r) = NS_r \cdot T_r = \frac{\bar{l}_r \cdot T_r}{\beta_r}. \quad (11)$$

As for the short user exposure, we have performed two linear regression analyses using *GPSTE* and *NPSTE*, respectively, as the independent variable and the short total exposure as the dependent variable. The results are shown in figures 9 and 10; parameter values are given in the appendix. In this case, the proxy based on geographic sparsity performs much better than the proxy based on network sparsity (adj.  $R^2 = 0.89$  for *GPSTE* and adj.  $R^2 = 0.72$  for *NPSTE*). The poor fit for *NPSTE* is mainly due to a small number of extreme outliers among the most exposed municipalities, which highly influence the result.



**Figure 9: Fitted regression line for GPSTE vs. short total exposure**



**Figure 10: Fitted regression line for NPSTE vs. short total exposure**

#### 4.5.3. Proxies for short importance

A region should be important if the detours generally are long and the links are heavily loaded with traffic. Therefore, the local sparsity of the network should again be an important component in a proxy variable. Rather than travel time, however, the average vehicle flow on the links in the region should also be included. In fact, we have found that weighing the link flows by the lengths of the links improves the proxies. The length weighted average link flow may appear difficult to acquire data for, but it is equivalent to the vehicle kilometres divided by the total kilometres of road in the region, for which estimates may be available. Using the geographic sparsity  $GS$  we get a proxy variable  $GPSI$  (“Geographic sparsity Proxy for Short Importance”), and using the network sparsity  $NS$  we get a proxy variable  $NPSI$  (“Network sparsity Proxy for Short Importance”). Formally,

$$GPSI(r) = GS_r \cdot \bar{f}_r = \sqrt{\frac{A_r}{L_r}} \cdot \bar{f}_r, \quad (12)$$

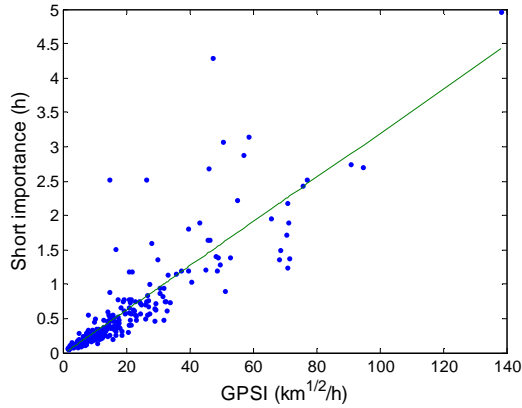
$$NPSI(r) = NS_r \cdot \bar{f}_r = \frac{\bar{l}_r \cdot \bar{f}_r}{\beta_r}, \quad (13)$$

where  $\bar{f}_r$  is the length weighted average link flow of the region.

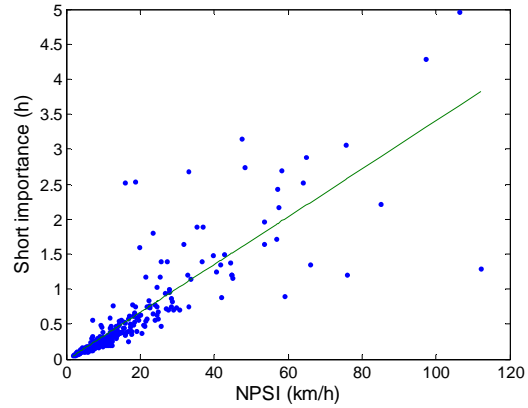
As before, we have performed two linear regression analyses of the municipalities using  $GPSI$  and  $NPSI$ , respectively, as the independent variable and the short importance as the dependent variable. The results are shown in figures 11 and 12; parameter values are given in the appendix. These proxies have less explanatory power than most of the proxies for short user and total exposure (adj.  $R^2 = 0.75$  for  $GPSI$  and adj.  $R^2 = 0.72$  for  $NPSI$ ). It is a matter for further research whether some modifications of these proxies would produce better results.

#### 4.5.4. Robustness analysis

The results found in the previous sections would be of little value if they depended heavily on the particular geographical partition of the road transport system that was used, in this case the municipality structure. To test the robustness of the results, we have repeated the regression analyses on the more aggregated level of counties (21 regions instead of 289). The results show that the proxy variables are very robust against this change of scale. Regressions of short user exposure on  $GPSUE$  and  $NPSUE$  give adj.  $R^2 = 0.77$  and adj.



**Figure 11: Fitted regression line for GPSI vs. short importance**



**Figure 12: Fitted regression line for NPSI vs. short importance**

$R^2 = 0.87$ , respectively. Regressions of short total exposure on *GPSTE* and *NPSTE* give adj.  $R^2 = 0.92$  and adj.  $R^2 = 0.98$ , respectively. Finally, regressions of short importance on *GPSI* and *NPSI* give adj.  $R^2 = 0.97$  and adj.  $R^2 = 0.93$ , respectively. The fits are thus better overall on the more aggregated county level than on the municipal level, which is hardly self-evident. Surely, there is a lower limit on the size of the regions, in relation to the detail of the road network and the travel distances of the users, below which these proxies based only on the regions themselves become too unreliable. The findings here may suggest that we when using the municipal system are approaching this lower limit, at least for some of the municipalities. Parameter values for all regressions are given in the appendix.

We find the regression results on the county level for the total exposure and the importance quite remarkable. The good fits for the importance are reassuring, since they were considerably poorer on the municipal level. We may also note that the proxies based on network sparsity perform better than those based on geographic sparsity in two of the three cases, while they performed worse in all cases on the municipal level. The reason for this shift remains a topic for further research.

## 5. Conclusion

We have presented a method for investigating the geographic patterns of road network vulnerability. Measures of regional exposure and importance have been defined and their distributions in the Swedish road transport system have been studied. The results show that there are considerable regional disparities in these measures, which tend to increase with the duration of the closure. The user exposure is the highest in sparse (in terms of both population and road network) areas, while the total exposure is the highest in dense areas, which is in line with expectation.

Further, we have found that regional exposure to a large extent can be explained by the sparsity of the regional road network and the initial travel times of the users. Correspondingly, regional importance can be explained by the sparsity of the regional road network and the length weighted average link flow of the region. These relationships hold on both the municipal and the county level, and they suggest that in order to decrease the exposure of a region one can seek to increase the density of the road network, or reduce the travel times of the users. The first of these objectives can be fulfilled by means of building new roads, for which the network sparsity measure tells us that many short roads are better than few long roads on average. More detailed analysis is required, however, to determine

the best location of a new road link in any particular case. The second objective can be fulfilled by all the means available to increase the efficiency of the road network, e.g., improving road standards, increasing maintenance and building new roads.

National road authorities are often required to consider regional development aspects in their planning processes, beside the overall socio-economic efficiency. The measures of regional exposure can be used as a basis for policy decisions such as the prioritization among different road projects and other investments. Authorities in particularly exposed regions can draw on them to promote decisions at the national level that would improve the situation in their own region. It is likely, however, that reducing the regional inequity of user exposure or that of total socio-economic exposure are strongly conflicting goals. The measure of regional importance, on the other hand, gives a general idea of in which regions a reduction of the consequences of a disruption would have the largest socio-economic benefits, an issue that should be of interest for planners at the national and regional levels. Again, decisions intended to increase the overall socio-economic efficiency are likely to conflict with the goals of reducing the regional user and total exposure. The analysis method presented in this paper allows the decision-making authorities to make well-informed decisions based on their prioritisations of these different objectives.

An interesting topic for future research is to perform the same type of analysis on other national road transport systems and analyse the similarities and differences. This could reveal to what extent the regional disparity of exposure and importance differs between countries. In particular, it would be interesting to investigate the universality of the proxy variables introduced here.

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## Appendix: Results from regression analyses

All regression models are of the form  $Y_r = \alpha + \beta x_r + \varepsilon_r$ , where  $r$  is the region (municipality or county),  $Y_r$  is the dependent variable,  $x_r$  is the independent variable,  $\varepsilon_r \sim N(0, \sigma^2)$ , and  $\alpha$  and  $\beta$  are parameters to be estimated.

**Table 1: Municipal level**

dependent var.	indep. var.	adj. $R^2$	param.	estimate	$t$ -statistic	$p$ -value
short user exposure ( $10^{-6}$ h)	<i>GPSUE</i> ( $\text{km}^{1/2}$ h)	0.87	$\alpha$	-1.1134	-4.4564	0.0000
	$\beta$		23.8439	43.9570	0.0000	
	<i>NPSUE</i> (km h)	0.83	$\alpha$	1.5094	6.4674	0.0000
	$\beta$		15.2212	37.8308	0.0000	
short total exposure ( $10^{-3}$ h)	<i>GPSTE</i> ( $\text{km}^{1/2}$ h)	0.89	$\alpha$	0.0427	1.1735	0.2416
	$\beta$		0.0093	48.5523	0.0000	
	<i>NPSTE</i> (km h)	0.72	$\alpha$	0.2364	4.2060	0.0000
	$\beta$		0.0080	27.5183	0.0000	
short importance (h)	<i>GPSI</i> ( $\text{km}^{1/2}/\text{h}$ )	0.75	$\alpha$	-0.0225	-0.7976	0.4258
	$\beta$		0.0322	29.2665	0.0000	
	<i>NPSI</i> (km/h)	0.72	$\alpha$	-0.0210	-0.7043	0.4818
	$\beta$		0.0343	27.4154	0.0000	

**Table 2: County level**

dependent var.	indep. var.	adj. $R^2$	param.	estimate	$t$ -statistic	$p$ -value
short user exposure ( $10^{-6}$ h)	<i>GPSUE</i> ( $\text{km}^{1/2}$ h)	0.77	$\alpha$	-0.2405	-0.3172	0.7545
	$\beta$		19.0954	8.2401	0.0000	
	<i>NPSUE</i> (km h)	0.87	$\alpha$	0.9405	2.1288	0.0466
	$\beta$		15.6597	11.6861	0.0000	
short total exposure ( $10^{-3}$ h)	<i>GPSTE</i> ( $\text{km}^{1/2}$ h)	0.92	$\alpha$	3.7097	2.8090	0.0112
	$\beta$		0.0068	14.7496	0.0000	
	<i>NPSTE</i> (km h)	0.98	$\alpha$	-1.4773	-1.7795	0.0912
	$\beta$		0.0105	28.6750	0.0000	
short importance (h)	<i>GPSI</i> ( $\text{km}^{1/2}/\text{h}$ )	0.97	$\alpha$	-0.0198	-0.9319	0.3631
	$\beta$		0.0271	25.8473	0.0000	
	<i>NPSI</i> (km/h)	0.93	$\alpha$	-0.2376	-5.4835	0.0000
	$\beta$		0.0457	16.8971	0.0000	