New Pratices in Vulnerability Assessment: Applicability and Limitations

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1 Abstract

This paper presents a methodology to assess link failure induced transportation related consequences including congestion related effects across a national network. The main challenge hereby considered is how to overcome the calculation time intensity of this equilibrium-based approach. Rather than employing the complete network for analyising a link failure, subnetworks are employed to model the spatially restricted demand shifts effects around a failed link. Each subnetwork is formulated by cutting a geographically defined selection of links and nodes out of the national network and including the internal and external demand traversing the subnetwork boundary. In an other paper describing the same piece of research it was shown that the failure consequences, even for links with long path distances or long detours, assessed with the subnetwork are very consistent with those considering the full network. This paper discusses the applicability, sensitivity and limitations of the approach are proved by Three selective case studies: It is demonstrated that the use of simplified networks, provided by current transport models, instead of high resolution networks has only minor impacts to accuracy. However, in some cases the consideration of subordinate network elements leads to more appropriate results and is therefore necessary. The paper presents a methodology how these cases can be detected and processed. Furthermore, an approach to detect links where the assumption of inelastic demand leads to substantial bias is presented and it is shown how the methodology can be extended for theses cases in a simple manner in order to include potential mode shifts.

2 Introduction

Infrastructure systems, such as transportation infrastructure systems, are composed of links connecting geographically dispersed communities, towns and cities. When these systems operate as designed, they form the foundation upon which commerce, trade and the serviced communities' can flourish. But when the availability of these systems is jeopardised by gradual deterioration (e.g. corrosion induced deterioration) or natural hazards (e.g. avalanche induced link failure), the communities they service can likewise suffer.

Over the past twenty years great strides have been made to address gradual deterioration of infrastructure objects (e.g. roads, bridges, tunnels) (e.g. (PONTIS (Thompson *et al.* (1998)), KUBA (Hajdin (2006))) the management of potential infrastructure failures due to natural hazard has not enjoyed a comprehensive or system-wide management perspective.

To integrate the natural hazards risk management into already existing management systems, one has to quantify the failure probability of a given infrastructure object to a given natural hazard and the resulting post-failure economic consequences. An approach to quantify such consequences across a national network and its applicability is presented in this paper.

This paper is organized as follows: Since an extensive literature review and a presentation of the methodology of this project is available in other papers (Erath *et al.* (2008), Erath and Axhausen (2008)) condensed information on these two points is quoted in Section 3. The approach is then applied for the Swiss case, presented in Section 4. The applicability and sensitivity of the results are then proven by three extensive case studies in Section 5. The paper ends with the conclusions and by formulating the needs for further research.

3 Foundation

3.1 Literature

The assessment of transport network failure consequences has attracted significant attention recently. The main focus of the relatively new notion i s not only to assess the actual state of transportation infrastructure but also the impact of a network deterioration to the community. Several definitions by different authors provide different perspectives on transportation related consequences including Berdica (2002), Taylor and D'Este (2003), Knoop *et al.* (2007), Matisziw *et al.* (2007). However, what they all have in common, is that they assess the impact of infrastructure failure, though with different measures and methodologies: Jenelius *et al.* (2006) neglects the traffic dependency of travel times, as the focus of their research was the Swedish road network with most parts of the country only sparsely populated and link capacity playing only a minor role in the analysis and therefore congestion becomes only a minor problem as result of link failures consequences. This might be a reasonable assumption for spatially disperse countries but Knoop *et al.* (2007) showed for the case of the Rotterdam metro region the need to include capacity constraints when analyzing road network failure consequences in more densely populated areas. What all mentioned approaches have in common is that they only consider route choice effects in the consequence failure assessment. The consideration of mode and destination choice effects is avoided due to higher model complexity while the accuracy gain is estimated to be rather small.

3.2 Methodology

3.2.1 Definition of Vulnerability

The consequences of inadequate performance can take two different forms: 1) direct consequences (CD) to the exposed component object in the form of structural damage including repair costs required to return the damaged infrastructure object to its pre-failure state and 2) indirect consequences (CI) to the transportation traffic by restricting or completely denying traffic flow including additional travel time and travel distance costs.

Thus, the vulnerability of component object i is the probability of component i experiencing failure due to a given hazard event ($P_{fi|E}$) multiplied by the sum of the direct and indirect natural hazard induced consequences (CD_i, CI_i respectively):

$$R_i = P_{fi|E} * (CD_i + CI_i), \tag{1}$$

with:
CD_i = the component object$_i$ direct financial consequences and
CI_i = the component object$_i$ indirect transport related failure consequences.

While the methodology to quantify the occurrence probability of hazard events and the direct consequence is presented in Birdsall and Hajdin (2008), this paper details the approach to quantify the indirect transportation related consequences of link failures, including congestion effects,within a national transportation network wide scale.

3.2.2 Assessing failure induced indirect transportation consequences

Using the concept of generalised travel costs, the impact of a link failure can be expressed as the increase in travel time and travel distance both multiplied by the duration of failure. Additional travel time and distance can, in turn, be converted into monetary units by multiplying each term with the willingness to pay for travel time reductions and the incurred average driving distance costs. Both values are also commonly used in cost benefit analysis and should therefore be readily available. The relevant figures for Switzerland are the outcome of recent studies (Hess *et al.* (forthcoming) and VSS (forthcomingb)): The willingness to pay for a travel time reductions equals 22.37 CHF/h and the average cost for driving is 0.5 CHF/km.

Formally, the indirect consequences of a link failure can then be expressed as:

$$\Delta TT_l = \Sigma_i \Sigma_{j \neq i} w_{ij} (c_{ij}^{(l)} - cij^{(0)}), \tag{2}$$

with
w_{ij} = Weight of relation zone i to j, assumed to be the demand,
$c_{ij}^{(0)}$ = Travel time from zone i to j under normal network conditions,
$c_{ij}^{(l)}$ = Trave time from zone i to j under modified network conditions with link l severed, to describe the additional post-failure travel time across the network and

$$\Delta TD_l = \Sigma_i \Sigma_{j \neq i} w_{ij} (d_{ij}^{(l)} - dij^{(0)}), \tag{3}$$

with
$d_{ij}^{(0)}$ = Travel distance from zone i to j in normal network conditions,
$dij^{(l)}$ = Trave distance from zone i to j in network conditions with link l severed and *indirect failure consequences* as

$$CI_i = \Delta TT_l \cdot C_{TT} + \Delta TD_l \cdot C_{TD}, \tag{4}$$

with
C_{TT} = the willingness to pay for travel time reductions,
C_{TD} = the average cost for driving a defined distance.

As Jenelius *et al.* (2006) pointed out, there are cases for which this approach assess additional travel time and distance but where some parts of the network might be divided from the rest which lead to $unsatisfied\ demand\ u_{ij}^{(l)}$, defined as

$$u_{ij}^{(l)} = \begin{cases} w_{ij} & \text{if } c_{ij} = \infty \\ 0 & \text{if } c_{ij} \text{ is} < \infty \end{cases}$$

Herein such network failure states are called *cut links* as a failure of such a link separates the network into two parts.

3.2.3 Inelastic Demand

To reduce computational complexity, only route choice effects are considered within this link failure assessment. Therefore, travel demand is assumed to be inelastic to mode choice and destination choice shifts. This approach has been chosen as it is assumed that the link closure duration will be long enough so that it can be assumed that all travelers are aware of the closed link and thus new equilibrium is reached. In addition, the failure induced additional travel cost per person are assumed to be small enough to not affect mode or even destination choice.

4 Implementation: Failure induced indirect transportation consequences in the Swiss road Network

4.1 The network of scope: The Swiss national Transport model

All calculations presented herein are based on the Swiss national transport model (Vrtic *et al.* (2005)), a two-dimensionally constrained disaggregate trip generation, distribution and mode choice model (Vrtic *et al.* (2007a)). The Swiss national model is implemented on the basis of 2949 small zones inside the country and 165 increasingly larger zones beyond the borders of Switzerland. It distinguishes seventeen combinations of six trip purposes for three modes (motorised private travel, public transport and the combined walking and cycling modes). It contains 30'289 undirected links of which are 19'804 within the Swiss territory as well as 24'316 (15405) nodes. The user-equilibrium assignment model software package VISUM 9.4 (PTV (2006)) was employed.

In the winter several mountain passes are closed an thus both summer and winter networks have to be considered representing two cases for the vulnerability when conducting this consequence analysis. The analysis presented in this paper is based on the winter network, since this state is relevant for the major part of the year.

4.2 Cut Links

As an initial analysis step, all links whose failure would lead to a cut off of a network part where detected. This was conducted by the temporal removal of each link and the search of the shortest path the two nodes the link connected before. If no path is found, the link is designated as a cut link, which was the case for 1555 links. Otherwise, the length of the shortest path was saved. Subsequently, the presence of rail detours alternatives was checked. For that purpose, the rail and road network were merged and for 97 links, an alternative path passing through rail links was found. Since here the assumption of inelastic demand is inappropriate, these links have to be assessed differently as presented in Section 5.1.1.

4.3 Subnetwork approach

The assignment of the Swiss national transport model takes, depending on the the speed of the computer and the chosen stop criterion of the equilibrium calculation, around 40 minutes (with an Intel Pentium 4, 3.2GHZ and 1Gb RAM). When multiplied by the total number of links, the calculation of transport failure consequences produced by the independent failure of each link would require 550 days of computation. To reduce computational intensity, knowledge about the characteristics of the transport demand is utilised: Due to network hierarchy, the main part of the links serves only little demand with rather short average path distances. Hence, the redistribution effects in dense parts are assumed to be spatially restricted and these indirect failure consequences can be modeled to a sufficiently accurate level using local subnetworks instead of the whole network. As the computational complexity of traffic assignment decreases exponentially with the decreasing number of links and zones, the calculation time gains of such an approach are substantial.

While the implementation of the subnetwork approach and the proof of this concept can be found in detail in Erath *et al.* (2008) and Erath and Axhausen (2008) this paper only sums up the main features and results: Two grid layers with 60 km edge length and an offset of half an edge length in x and y axis were overlayed the Swiss transport model. According to the two grids 140 subnetworks were cut out. One negative byproduct of employing the subnetwork generation is that certain links became cut links within the new subnetwork as the shortest detour extends beyond the boundaries of the subnetwork. Such links, commonly located in the mountainous regions of Switzerland, are characterised by long path lengths and low local density resulting in large scale detours. Therefore subnetworks for each of the two Swiss mountain ranges, Alps and Jura, were generated.

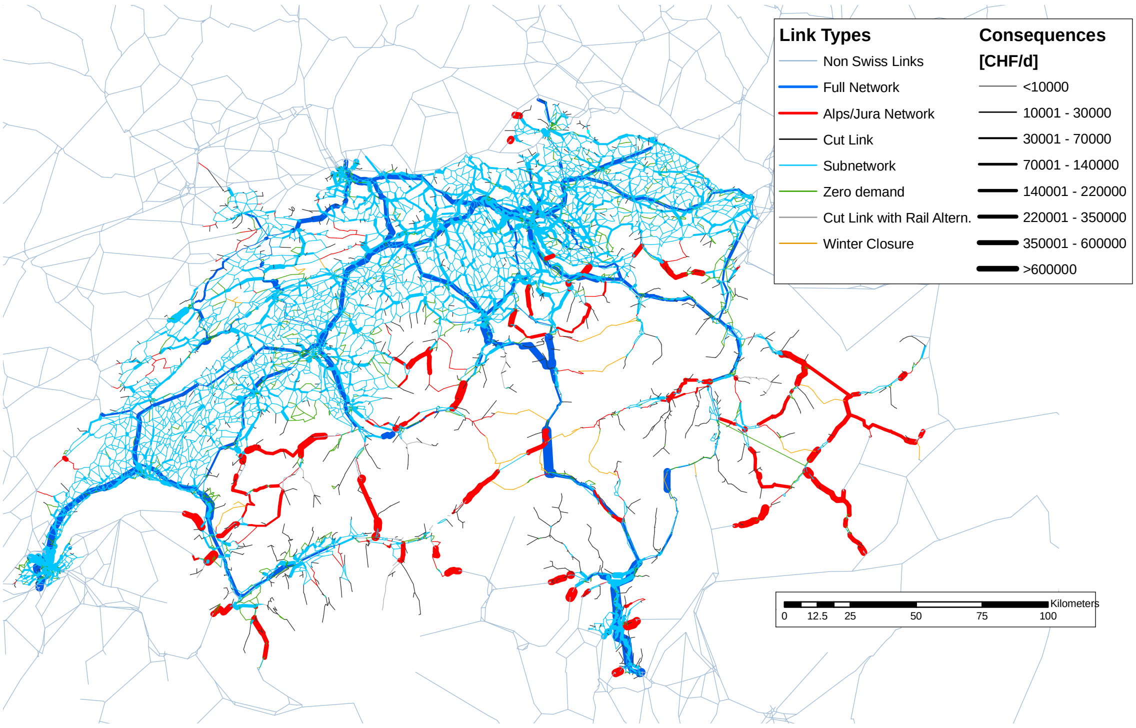
Since motorways are links of high hierarchy characterised by high volumes as well as long average path lengths its failure can lead to sever local congestion and hence to large scale detours. Therefore, motorway links were assessed using the entire network.

4.4 Transport Related Failure Consequences

Figure 1 shows the applied methodologies for all links in the considered network and the magnitude of the indirect failure consequences by line width for all non-cut links in the Swiss national model. Motorway links and links with long detours which were assessed by the Alps and the Jura networks have the highest impact: the first mainly because of the volume which has to be redirected, the latter because of the long detour distances.

The highest consequences are found for the Simplon and Gotthard north-south Alp tunnels with a loss of 1.3 and 1.1 millon CHF/day respectively, followed by the motorway passing by Monte Ceneri (0.97 Mio CHF/day) which all are also served by rail tunnels. For 18 of the 20 most severe cases, a rail alternative is also present, which suggests that the calculated values should be considered as an upper limit. However, in regions where the rail system operates already at capacity and would therefore not be able to absorb the new demand, it is reasonable to expect the real value not to be substantially smaller than the current value.

Figure 1: Indirect failure consequences (link width) based on the Swiss National Transport Model



5 Case studies

5.1 Inelastic Demand

5.1.1 Cut link with rail alternative: The Grindelwald case

The assumption of inelastic demand is applicable if the additional travel time/distance for a given person is small. However, the failure induced detours for some links, especially in the mountainous regions, is rather long or even not existing (cut-links). The objective of this case study is to present a methodology to detect such failure scenarios and to estimate its consequences in monetary terms.

As an example how such a scenario can be evaluated this case study analyses the failure of the road connecting Grindelwald with Zweilütschinen and Interlaken. Without consideration of the railway line the result of this scenario would be the cut off the villages Grindelwald and Lütschental from the rest of the network. As the assumption of inelastic demand is apparently not appropriate, an approach to quantify the costs of such settings must incorporate the costs related to a mode shift.

The estimation of the mode shift cost is twofold:

- The difference of generalised costs between privat transport under normal network conditions and public transport
- A certain disutility caused by the forced mode shift

The generalised costs involve the normal travel cost but also travel time costs and in the case of public transport transfer and and access/egress costs. These costs are taken from the Norm SN 640 822a (VSS (forthcomingb)) which are derived from an extensive willingness to pay study (Hess *et al.* (forthcoming)). The running costs for cars are assumed to be 0.5 CHF/km (VSS (forthcominga)) with an occupation rate of 1.58 passengers per vehicle and the public transport ticket costs to be 0.25 CHF/km (Vrtic *et al.* (2007b)). In order to obtain a conservative value, the disutility of the forced mode change is only composed of the additional access/egress time linked to the mode change and does not contain any other imposition.

Table 1 summarises the key figures of the cut link failure consequence assessment for the Grindelwald valley case. For consistency reasons, the calculation includes only trips with origin or destination within Switzerland: International trips are based on the border crossing survey (Swiss Federal Department for Environment, Transport, Energy and Communication and Swiss Federal Office for Spatial Development (2001)) while all other trips are based on a trip gener-

Table 1: Cut link failure consequences: The Grindelwald case

	Grindelwald	Lütschental
Demand origin/destination [passengers/d]	3798	377
Average path distance [km]	39.7	17.2
Cumulated car cost under normal condition [CHF/d]	95’622	4’235
Cumulated costs for substitute trips by PT [CHF/d]	149’181	10’289
Costs forced mode shift [CHF/d]	23’233	2’489
Total failure consequences [CHF/d]	76’791	8’544

ation model. Moreover, it is expected that the occupation rate of these predominant touristic trips and hence the running costs per person are substantially different.

Compared to failure consequences which involve only route choice effects these values are comparable to a failure of motorway links with reasonable volume like the parts of the A2 between Emmen and Neuenkirch, the J18 near Münchenstein or the A6 near Muri bei Bern.

Further effects of such a failure which could appear as destination choice shift or the suppression of trips are not included. Qualitatively, the inclusion of destination choice shifts would alleviate the failure induced costs, since users would only change their destination if the associated costs are less than the costs associated to the mode shift. On the other side, the exclusion of trip suppression overestimates the effects: If the benefit of a person of doing an activity is less than the new trips costs, this person would skip this activity. However, in the context of this study it is not feasible to estimate the real benefit of an activity for a given person.

In addition, secondary effects of changes of destination choice or the suppression of trips such as sales shortfalls are also not be included in the proposed methodology. On the other hand, it is expected that short term mitigation measures such as the offer of train car train carriages can reduce the failure consequences.

To identify other cut links with rail alternative, for all cut-links it was scrutinized if a rail alternative is available. This was done using a merge of the road and the rail network to recalculate the shortest detour considering both networks. Cut-links with rail alternatives are mapped and orange colored in Figure 2. These links account for 0.4% network length share.

5.1.2 Long detour with rail alternative: Still inelastic demand?

But not only the failure of cut links with rail alternatives may lead to mode shifts. The failure induced detours for some links, especially in the mountainous regions, are rather long. For these cases, given a road link failure, the expected demand reaction would be a mode shift from car to rail rather than a change of the destination choice or the suppression of trips, respectively. To detect for which link failures the presence of rail alternative might have a substantial influence on the consequences, a systematic analysis was conducted.

The failure induced additional generalised costs per person are compared to a lower limit of the user costs related to a mode change. It is assumed, that a person won't change his travel mode in response to a link failure unless the additional costs exceeds the costs related to the mode shift. This threshold can be set by indicating the increase of generalised costs to be the sum of the disutility of the forced mode change, the access time, the expected waiting time, the difference of travel time and cost and possible transfers.

The most recent evaluation for the Swiss case of such values can be found in (Hess *et al.* (forthcoming)). In order to avoid the need of collecting origin-destination related public transport trip information, the threshold must be generic and not related to a given origin-destination relation. Therefore, and to obtain a conservative threshold, only the following elements of generalised cost, are considered:

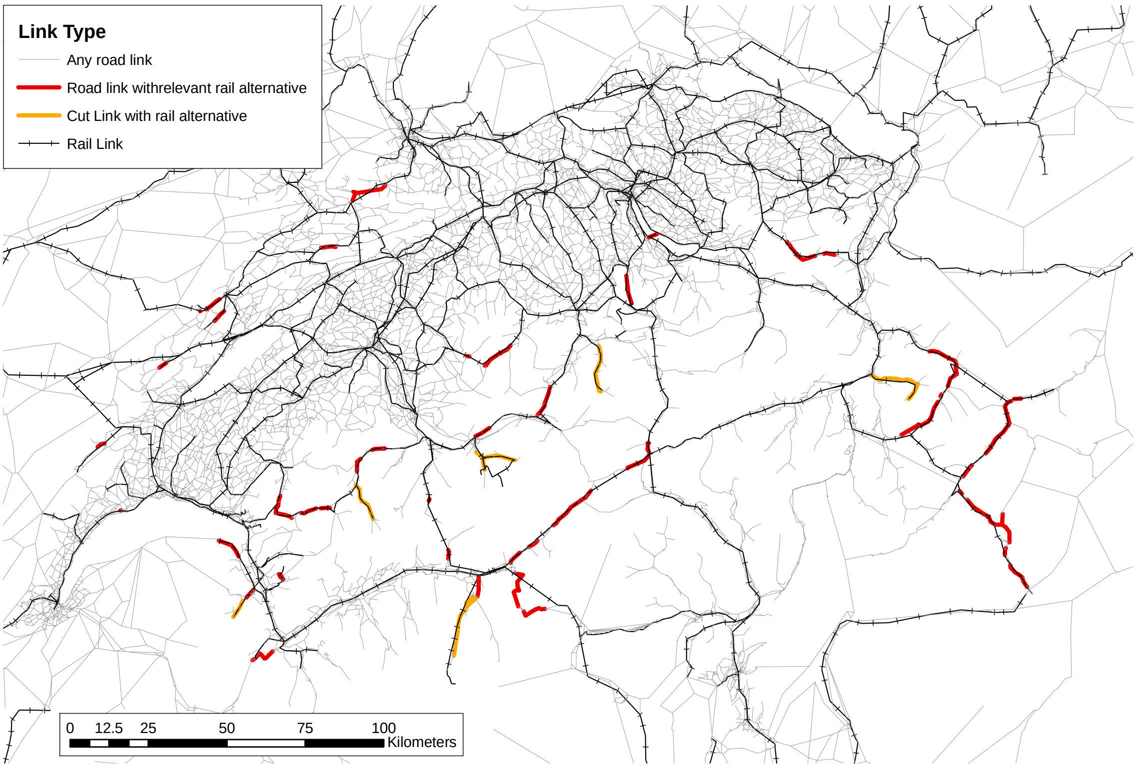
- An access and egress time of 10 minutes ($10 * 0.38$ CHF/min),
- 0.5 transfers ($0.5 * 2.34$ CHF/min),
- with a transfer time of 5 minutes ($5 * 0.5 * 0.10$ CHF/min).

Hence, only in cases with failure induced additional user costs per person higher than 5.25 CHF, a mode shift might be relevant which is is the case for 1'364 links.

In a next step travel time differences between public transport trips and car trips were estimated using the average path distances of theses links. For this purpose, average speeds of 60km/h for car trips and 30km/h for public transport trips were assumed. These figures are higher than what has been reported by Fröhlich (2008) for commuter trips (car trips: 47.95 km/h; public transport: 21.46 km/h, with average trip length of 11.54 km and 12.25 km, respectively). However, the path average path lengths of the relevant links is longer than the reported figures (42.69 km) and it is assumed that with longer trip distances the speed level increases and the relation of average speed changes in favor of public transport. With this data the user cost of a trip with average distance by public transport is calculated and compared to failure induced additional cost per person, calculated without consideration of rail alternatives. In 662 cases the user costs by public transport were smaller.

Up to this point, the analysis did not consider if a meaningful rail alternative is actually available. Therefore, it was visually checked whether an rail line offers a meaningful alternative to the failed road link. Finally, 218 links were detected whose failure is considered to above

Figure 2: Links for which the assumption of inelastic demand is not applicable



criteria which are mapped in Figure 2 and red colored. These links account for a link length share of 1.4%.

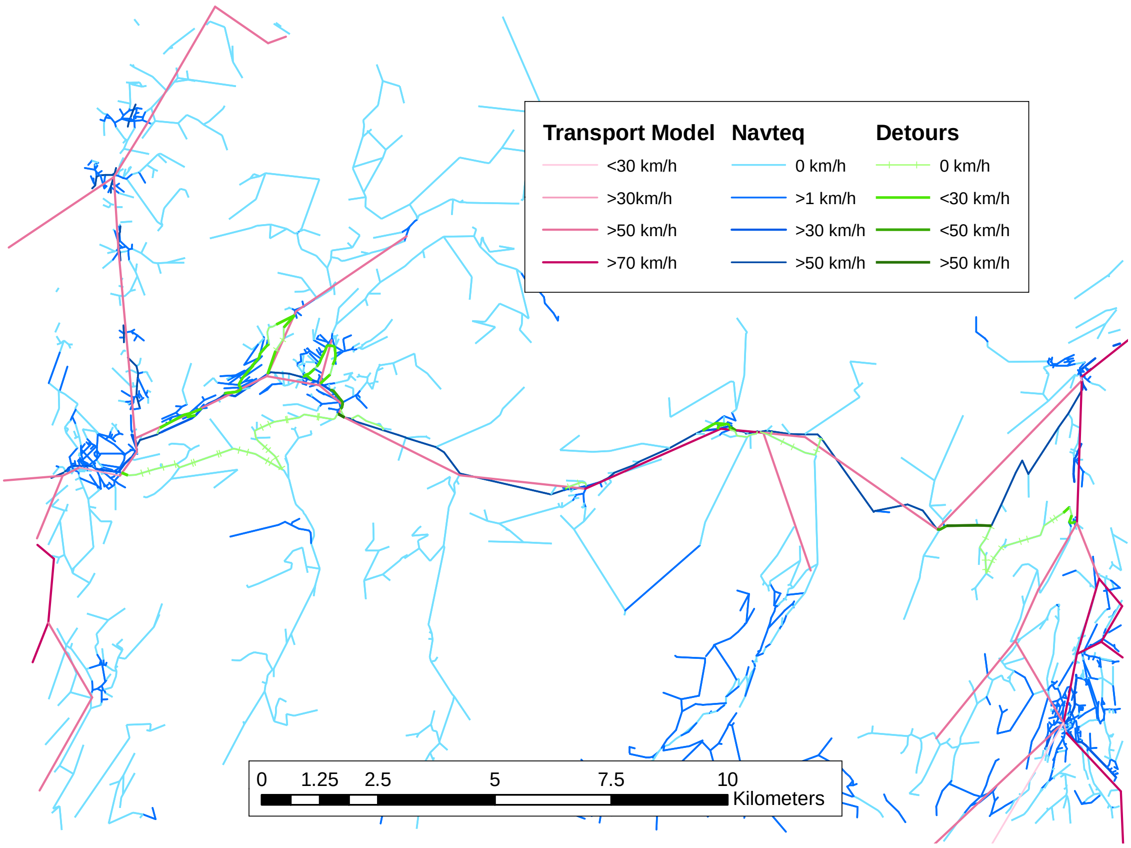
In order to indicate the failure induced user costs for links whose failure is assumed to lead to mode shifts, an integrated multi-modal transport network has to be set up. This was not available at the time of writing but is subject of on-going work.

5.2 Simplified Network

5.2.1 Jaunpass: Is the network resolution sufficient in rural parts?

The Jaunpass connects Gruyères with the Simmental and Spiez and is a typical connection of two prealp valleys. In the network of the Swiss national transport model the road infrastructure is represented only by the main trunk road while smaller access roads are not covered. The volume assigned to these links is with between 850 and 2535 cars/day rather low and at least some of the smaller access roads would have the capacity to serve this volume without substantial congestion effects. Therefore, these access roads could provide relevant alternatives to the main road in case of failure. This case study identifies the potential of such access roads

Figure 3: Jaunpass: Overlay Swiss Transport Network - Navteq



to reduce the failure consequences exemplarily. Figure 3 shows an overlay of the road network used in the Swiss national transport model and the Navteq network which is a high resolution network normally used for GPS applications. As expected, the Navteq network covers some links which may serve as detours.

However, the attributed speed of most of these links is 0 km/h indicating that on these links general motorised traffic is banned. If the main road fails, such links are restricted to emergency or basic supply traffic as the Engelberg case in 2005 showed. However, on this level of scope, a definitive judgment cannot be delivered without knowing the local situation. Nevertheless it is important to analyse where else the neglect of local alternatives may have biased the failure consequence assessment. Since it is not possible to conduct such checks for the whole network manually (reliable network matching algorithms are still not available, (Balmer *et al.* (2005))) or to employ the Navteq network for the analysis, a certain prioritisation had to made by setting a borderline: Only for those links with shortest detours longer than 30km, the availabilty of local alternatives (provided by links where general motorised traffic is allowed) is checked by employing the the Navteq network.

In 120 of 628 cases, local detour links initially not included in the network were identified by analysing the GPS map data. For these links, the failure consequences measure was recalculated resulting in substantially smaller values.

5.2.2 Zofingen: Is the network resolution sufficient in agglomeration regions?

Non considered local roads may not only provide relevant detour alternatives but also additional capacity in cases where the failure leads to congestion. But because of the small capacity and the low hierarchy in the network of these access roads, this bias is considered to be small. To affirm this assumption, the subsequent case study quantifies the bias of using a simplified network.

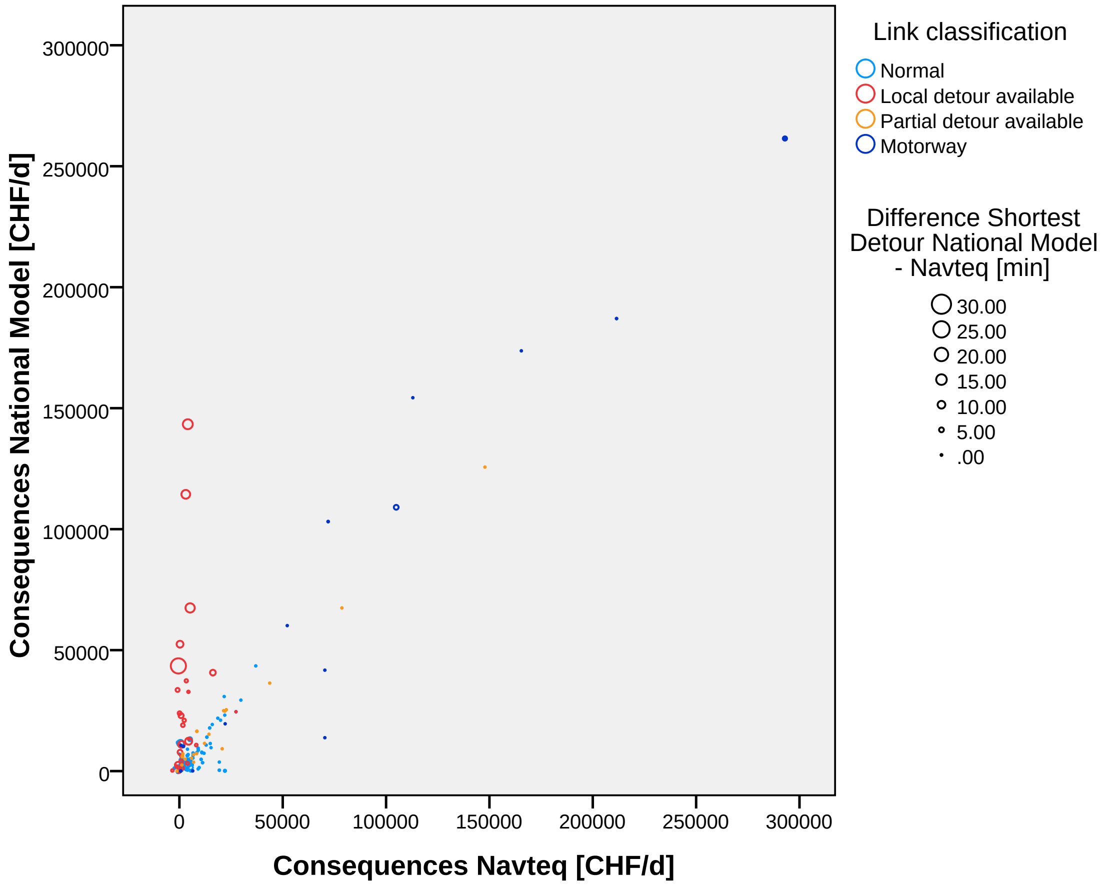
The region around Olten/Zofingen in the Swiss plateau with its small and mid-sized municipalities can be considered as representative in terms of network density and population distribution characteristics for a main part of Switzerland. Additionally, the crossing of the main north-south and east-west motorway corridors is also located here, giving the opportunity to assess the bias of using a simplified network also for high hierarchy links.

For this case study, the simplified road network of the relevant 30km subnetwork was exchanged with the same digital map network (Navteq) as above in the Jaunpass case. Instead of 685, the new network contains 25'784 undirected links for the given subnetwork. The demand model was entirely adopted from the already existing subnetwork. Only the connectors between the demand zones and the new network had to be newly generated, whereby it was ensured that the new and old nodes were in accordance. Finally, the link type characteristics were harmonised, adapting the links speeds and capacity of the simplified network to the Navteq network.

To compare the results calculated with the two different networks, the functional counterpart to every link of the simplified network in the Navteq network had to be detected. One difficulty thereby was that one link of the simplified network was normally represented by a bunch of links in the Navteq network whereas some of these links can be circumnavigated in proximity and others not. In such cases the link matching considered the length of the corresponding links. If a majority of the corresponding links in the Navteq-network is served by a detour in proximity, the link from the simplified was assigned to such a link and vice versa.

Since a square subnetwork with 30km edge length was employed only the links within the inner 15km square of the subnetwork containing 235 directed links is reanalysed. 13 links representing motorway ramps were not considered, since they are differently modeled in the two networks (directed in the Navteq, undirected in the simplified network). For the remaining 222 links the failure consequences were calculated. As a result of the higher network resolution the calculation increased by a factor of seven. Figure 4 shows the comparison of the failure

Figure 4: Failure consequences based on different networks



consequences on a scatterplot.

The scatterplot reveals the dependence on the detour distance. For links which can be detoured by using circumjacent access roads which are not covered in the simplified network, the calculated failure consequences are substantially different (red dots). For all other links, however, the results are very comparable. This highlights the relevance of the mentioned ambiguity in the counterpart detection if a link of the simplified network is represented by several links with different detour characteristics in the Navteq network (orange dots in Figure 4). Here, the exact location of the failure determines the real failure consequences. On the other hand, it is expected that such local detours primarily available in agglomerations, whereas in more rural regions detours are only present within the villages but not for links connecting them.

Given the need to compute failure consequences across a national network, the use of a digital map networks would increase the computation intensity too much and one would not be able anymore to run the analysis on a standard desktop computer in reasonable time. However, the case study showed that the failure consequences can be substantially overestimated even for links with shorter detours than 30km. Therefore it is recommended to scrutinise the presence of local alternatives at least for these links whose failure induced consequences is appraised to be substantial.

6 Conclusion

This paper presents an new approach for calculating transport related failure consequences including congestion effects across a national network. This approach is based on three assumptions:

- Limited spatial impact of failure consequences,
- No consideration of mode or destination choice effects.
- Use of a simplified network,

The applicability of the approach was assessed successfully, although certain shortcomings linked to restriction of covering only route choice effects and the use of simplified networks were detected:

The assumption of inelastic demand could be proven for the vast majority of links. But for a limited number of links, located in the mountainous parts of Switzerland, the assumption was disproved. A methodology how failure consequences can be estimated in such cases was successfully implemented for the case of Grindelwald but remains to be applied for the entire network.

In general, the bias caused by employing a simplified network instead of the complete road network can be considered as small. However, for some links the complete network offers relevant alternatives reducing the failure consequences substantially. These links are located in less dense parts of the network. As their number is limited, a post-processing assessment is feasible and recommended. However, a case study showed that even in dense parts of the network the relativ bias may be considerable. But since the absolute figure of failure consequence is still comparatively small and the use of a complete network would multiply the computation time many times, it is recommend to use simplified networks to indicate indirect failure consequence measures across a national network an to reanalyse only those links with high values.

In this study each failure is assumed to be mutually exclusive. This is a potential gross simplification for certain types of natural hazards such as floods, avalanches and torrents. Since the calculation of all possible link failure combinations is not feasible, it would be only reasonable to calculate joint failure consequences of link combinations exhibiting a high mutual occurrence, derived from the analysis of the hazard maps, which is a piece of information currently not considered nor collected by the hazard assessment field. One alternative potential approach would be to try to identify link failure combinations which induce the most severe consequences to state an upper limit of failure induced consequences.

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