

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/245563801>

Vulnerability Assessment Methodology for Swiss Road Network

Article in *Transportation Research Record Journal of the Transportation Research Board* · December 2009

DOI: 10.3141/2137-13

CITATIONS

83

READS

924

4 authors, including:



Alexander Erath

Singapore ETH Centre

64 PUBLICATIONS 680 CITATIONS

[SEE PROFILE](#)



Kay W. Axhausen

ETH Zurich

643 PUBLICATIONS 11,393 CITATIONS

[SEE PROFILE](#)



Rade Hajdin

Infrastructure Management Consultants GmbH

66 PUBLICATIONS 313 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Population Synthesis [View project](#)



Investigation of the relationships between MPSD* trips, land use and sustainability in transportation (*Multiple Purpose at a Single Destination) [View project](#)

Vulnerability Assessment of the Swiss Road Network

—

Alex Erath

Institute for Transport Planning and Systems (IVT), ETH Zurich, CH-8093 Zurich

phone: +41-44-633 30 92

fax: +41-44-633 10 57

erath@ivt.baug.ethz.ch

James Birdsall

Infrastructure Management Consultants LLC, Signaustasse 14, CH-8008 Zürich

phone: +41-43-497 95 20

fax: +41-43-497 95 22

james.birdsall@imc-ch.com

Kay W. Axhausen

Institute for Transport Planning and Systems (IVT), ETH Zurich, CH-8093 Zurich

phone: +41-44-633 39 43

fax: +41-44-633 10 57

axhausen@ivt.baug.ethz.ch

Rade Hajdin

Infrastructure Management Consultants LLC, Signaustasse 14, CH-8008 Zürich

phone: +41-43-497 95 20

fax: +41-43-497 95 22

rade.hajdin@imc-ch.com

Words: 6597+ 2 tables + 2 figures => equivalent word count: 7597

ABSTRACT

This paper presents a methodology for **integrating vulnerability** due to natural hazard into current infrastructure management systems. It is mainly concerned with presenting 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 via equilibrium. Rather than employing the complete network for analysing 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 select of links and nodes out of the national network and including the internal and external demand transversing the subnetwork boundary. 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. A statistical model, highlighting and detailing the key factors defining transport related consequences, is developed from the computed link failure consequences and link parameters. Lastly, the findings highlight the potential gains to be derived from directly including rail networks and covering the potential mode shifts in the assessment.

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). Given the scale of today's transport network infrastructure management systems (IMSs) like PONTIS (Thompson *et al.* (1)) or KUBA (Hajdin (2)) have been developed to collate inspection data, model and predict future deterioration processes, and develop optimal infrastructure management approaches. On the other hand, the management of potential infrastructure failures due to natural hazard has not enjoyed a comprehensive or system-wide management perspective. The most common approach is to conduct localized or regional transportation natural hazard risk assessment and mitigation projects. These activities commonly follow natural hazard events and result in localized management and mitigation approaches. A number of large-scale systematic risk assessment initiatives, including Risk Map Germany (Tyagunov *et al.* (3)) and Riskscape New Zealand (King and Bell (4)), are under development but only one platform, the United States Multi-Hazard platform HAZUS-MH (Federal Emergency Management Agency (5)) has been implemented for systematically assessing risk from a national viewpoint. However, 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.

Although in transport literature the term "vulnerability" is usually used to describe the transport related consequences, like additional travel times, distances or decreases in accessibility it is herein argued that vulnerability needs to be considered as a combination of the occurrence probability of a given hazard, the resistance of the structure against the hazard and the resulting consequences to transport.

This paper is organized as follows: The next section presents recent approaches to quantify transport related link failure consequences and builds the basis of the methodology development presented in the subsequent sections. The discussion of the results includes an analysis of the accuracy of the applied approach. Given the enormous computational intensity and required high quality of input data, the results were used to derive a statistical model to more straightforwardly describe network failure consequences. The paper ends with the conclusions and the needs for further research.

LITERATURE

The assessment of transport network failure consequences has attracted significant attention recently. The main focus of the relatively new notion is to assess not only the actual state of transportation infrastructure but also assess the impact of a network deterioration to the community. The increasing frequency of natural hazards due to global warming (Schneider *et al.* (6)), recent collapses of transportation links like in New Orleans and Switzerland due to natural hazards and the threat of terrorist attacks enhances the relevance of the topic. Nevertheless, the research community has not reached a common definition of link failure induced transportation related consequences. Several definitions by different authors provide different perspectives on transportation related consequences including (Berdica (7); Taylor and D'Este (8); Knoop *et al.* (9); Matisziw *et al.* (10)). However, what they all have in common, is that they assess the impact of infrastructure failure, though with different measures and methodologies: For instance (Bell (11)) and (Bell and Cassir (12)) have used a game theory approach and formulated the problem as a 2-player, noncooperative, zero-sum game envisaging between a router, seeking a least-cost path, and a virtual network tester, seeking to maximize transportation consequences by severing one link at a time. Thereby, this approach was applied to identify the most vulnerable network elements. However, when link costs are assumed to be traffic-dependent, which they are, such a methodology is very computationally intensive and is only applicable within small networks. Besides Monte Carlo Simulation (Chen *et al.* (13)) and Minimum Cut Set (Iida and Wakabayashi (14)) particularly approaches which incorporate both the demand and supply side of traffic assignment models were used recently for the assessment. They differ mainly in the type of traffic assignment used: Jenelius *et al.* (15) 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 congestion therefore 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.* (9) 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.

However, a major constraint using traffic assignment models for analysing of transport related failure consequences is the computational intensity. As each link failure scenario has to be calculated separately and the calculation time for one equilibrium assignment for the Swiss network with over 20'000 links and 3'110 zones takes about 40 minutes, it is obvious that alternative approaches have to be addressed. This problem has also been identified by the research community and some researches have subsequently attempted to describe and forecast the vulnerable parts of a network with various indicators (Knoop *et al.* (16)). These indicators include different measures of volume and volume/capacity ratio, the number of paths over a link, spill-back figures and also a step function to ensure that also less traveled but may be topologically important links are considered. These indicators were assessed on correlation between each other and rank order against the results of the full assignment. Unfortunately the results had no comprehensive explanatory power; especially the rank order test, which analyses if the indicators rank the same links on top of the vulnerability list than the assignment, lacked the necessary significance. Scott *et al.* (17) calculated the additional travel time due to link failure in three generic transport networks using Wardrop's user equilibrium principles (Wardrop (18)) and named the result as the network robustness index (NRI). The intention was to prove that it can be more efficient to provide additional routes links and transportation capacity not only at known bottlenecks but also rather at vulnerable link failures because of missing alternative paths. This research showed some significant correlation between the volume/capacity ratio

and the NRI, but reveal, like Knoop *et al.* (16), important differences between the selections of the most vulnerable links by the different measures when they are assessed by rank order. 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.

METHODOLOGY

Definition of Vulnerability

In the field of infrastructure management systems risk is expressed as the probability of occurrence of a given event multiplied by the failure probability of a given infrastructure object due to this event and the corresponding consequences. To integrate natural hazards, both the probability of inadequate performance and the related consequences have to be considered. 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.

The vulnerability of component object i , is thus 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):

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

with:

CD_i = the *componentobject_i* direct financial consequences and

CI_i = the *componentobject_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 (19), 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.

Assessing failure induced indirect transportation consequences

Indirect consequences must be quantified in monetary units so that they may be implemented into the framework of an infrastructure management system. From the different approaches to assess transport related consequences of failures, only those whose measures can easily be converted in monetary units are suitable. Using the concept of generalised travel costs, the impact of a link failure can be expressed as the increase in travel time and 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.* (20) and VSS (21)).

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

$$\Delta T T_l = \sum_i \sum_{j \neq i} w_{ij} (c_{ij}^{(l)} - c_{ij}^{(0)}), \quad (2)$$

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,

$c_{ij}^{(l)}$ = Travel 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

$$\Delta T D_l = \sum_i \sum_{j \neq i} w_{ij} (d_{ij}^{(l)} - d_{ij}^{(0)}), \quad (3)$$

with

$d_{ij}^{(0)}$ = Travel distance from zone i to j in normal network conditions,

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

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

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.* (15) 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.

The network of scope: The Swiss national Transport model

All calculations herein presented are based on the Swiss national transport model (Vrtic *et al.* (22)), a two-dimensionally constrained disaggregate trip generation, distribution and mode choice model Vrtic *et al.* (23). 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 (24)) was employed.

The network used in the model is a simplification of the complete Swiss transportation network and contains only the relevant links for inter communal travel demand but not all access roads. Non considered local roads may provide in case of failure of an larger road relevant detour alternatives. But because of the small capacity of these access roads with slow speed this bias is considered to be small. A sensitivity study of this resulting overestimation is currently underway, but conclusive findings were not available at the time of writing. Nevertheless, in more remote places, such as in mountain valleys, these roads have the potential to offer alternatives around cut links which were detected based on the simplified network. Therefore, when links with high traffic consequences are identified the presence of local alternatives is checked for links with high failure consequence figures in these regions employing GPS navigation networks as provided from Navteq or Teleatlas. In the winter several mountain passes are closed and 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.

Cut Links

According to the definition above, the transport failure consequence measure is only defined for links with assigned demand. Hence, links with zero assigned demand are excluded from this analysis. However, it is clear that all links serve some traffic demand but since demand is assumed to be very small, the failure consequences are also considered to be very small as compared to those of links with assigned demand.

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. For 97 links, an alternative path passing through rail links was found.

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.

A subnetwork is a limited section cut from the complete network including the section's internal and transit demand. To generate the subnetworks, 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. Afterwards, the subnetworks were cut according to the two grids, resulting in 140 subnetworks. The same procedure was repeated with using a grid of 30km edge length generating 476 subnetworks. Therefore it could be assured that every link is at least 15km or 7.5km respectively from the nearest 60km or 30km subnetwork border. 30km edge length subnetworks) afar. As the computational complexity of traffic assignment decreases exponentially with the decreasing number of links and zones, the calculation time gains are substantial. The average calculation time for one failure consequence assessment using the 60km and the 30km subnetworks took 35 seconds and 12 seconds respectively.

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. These mountain range networks were also extended to include parts of the adjacent plateau to ensure the shortest paths were included.

Three factors were taken as proxies for the spatial impact of a failure: the normal state average path length, the link volume and the shortest detour of the failed link. Therefore, in addition to recording of the shortest detour and the volume, for each link, the mean and standard deviation of the path length were also calculated and recorded. The analysis revealed that especially links ranked high in the functional hierarchy, such as motorways, exhibited at

TABLE 1 Assessed link characteristics, separated by employed link analysis methodology

	Full Net.	Alps/Jura	Subnet.	Cut Links	Cut Links II	No dem.
Number of assessed links	1243	689	14613	1555	97	1976
Average Volume	12263.7	1460.4	2468.7	245.5	1615.7	0
Std dev. Volume	9634.8	1395.4	2851.3	965.9	165.8	-
Average Path Distance	62.7	46.5	21.4	6.89	32.2	-
Std. dev. Path Distance	41.8	25.5	13.5	16.5	14.1	-
Average length detour	8.12	85.5	6.5	-	(7.7)	9.9
Std dev. length detour	11.0	53.7	5.4	-	(4.5)	22.7

least the two of the three criteria - long path lengths and high demand. In case of failure, severe local congestion is expected. Therefore the new shortest path for some long distance OD-relations may be a large scale detours which only can be captured by employing the entire network. Organizationally, the Swiss road infrastructure is classified in national, cantonal and municipal roads. National roads carry typically a high traffic demand with long average path distances. Therefore, this category is assessed with the full network approach. All links which are not part of the national network but which have shortest detour lengths longer than 30km are assessed with either the Alps or the Jura network.

Figure 1 shows the applied methodologies for all links in the considered network and Table 1 summarises the key figures. The bulk of the links are assessed with the subnetwork approach which show the shortest average detour distances. The links, analysed with the full network is employed have, by far, the highest average volume, while the links assessed with the Alps and Jura network have the longest detours. Cut links without rail alternative serve on average only a limited demand, whereas cut links with a rail alternative (named cut links II in Table 1 are similarly characterised as the links assessed with the Alps/Jura network.

Inelastic Demand

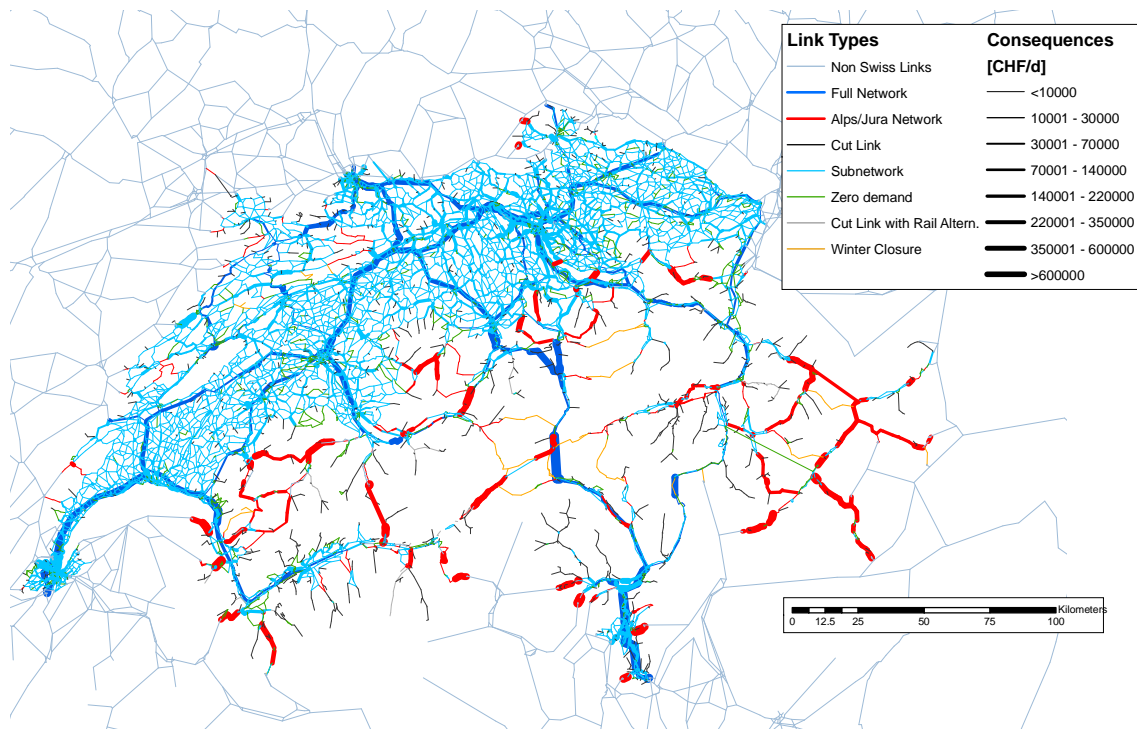
To reduce computational complexity, only route choice effects are considered within this link failure assessment. Therefore, travel demand is assumed to be inelastic to mode choice and destination choice shifts. This approach has been taken as it is assumed that the link closure duration will be long enough so that it can be assumed that all travelers are aware of the closed link and thus can reach a new equilibrium and is short enough to not affect mode choice or even destination choice. This assumption should be reasonable for a dense transport infrastructure network such as the Swiss network. However, cut links in the mountainous regions have to be reanalysed to consider the influence of potential rail links. As it is common for travelers to shift transportation modes, rather than completely delete a trip, these links have been highlighted for future analysis.

Consideration of Rail Infrastructure as Additional Redundance

Although demand is assumed to be inelastic, the presence of an alternate mode has to be taken into consideration as this has significant influence on the employed failure consequence assessment. Several valleys in the Swiss mountains have no through access but some are served both by road and rail. 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. The assessment of such road links is different from the 'normal' links, as the cost

of the imposed mode shift must be included. As this assessment scheme would require the estimation of the costs of the forced mode shift and the incurred public transport fares this project currently focuses on just identifying such links for future analysis.

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



RESULTS

Transport Related Failure Consequences

Figure 1 presents 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. However, for the majority of the links, a failure induces only minor additional travel times as the volumes are low and the surrounding networks are dense. For 2239 links, all with only small demands assigned, negative additional travel times were calculated. It could be verified that the negative additional travel times were caused by rounding errors. The comparison between the normal and the failure network of such cases revealed redistribution effects in area adjacent to the failed link but also in geographically distant areas with links of high volume capacity ratio but none in between. Even when stringent stop criteria is employed, the steep slope of the capacity restraint function induces significant volume changes on these links and its detours on between two subsequent assignment iterations. Approaches to restrict the analysis scope in order to exclude such irrelevant demand shifts were tested but have not produced satisfactory results at the time of writing but are subject of on-going work.

The links with the highest values are located in the upper Valais, a mountainous region serviced by a single main valley. In the model, a failure of one of the main valley links cuts this functional region apart. This reveals two critical issues of the applied approach: First, the neglect of low hierarchy links in the assignment model necessitates the inclusion of a post processing analysis to check for local transportation link alternatives. Secondly, the assumption of inelastic demand in term of mode choice is only valid as long the additional travel time/dis-

tance for a given person is small. As in the case of the upper Valais which is also served by rail, one would expect the reaction to be a mode shift towards rail in order to significantly limit the incurred consequences. These non-considered local alternative and multi-model post process checks were employed to verify the results for the links covered by the Alps/Jura-network. In 120 cases, local detour links initially not included in the national model were identified by analysing the GPS map data. For these links, the failure consequences measure was recalculated resulting in substantially smaller values. 108 links were detected to have a rail alternative with sufficient capacity and omitted for the further analysis.

Finally, the most exposed link in terms of additional travel time is the motorway section passing by Monte Ceneri and serves as a main European north-south corridor. The only available alternative, within reasonable distance, is an old trunk road whose capacity is too small to carry the rerouted traffic with an adequate service level. Its failure would induce additional travel time per day of 37'155h.

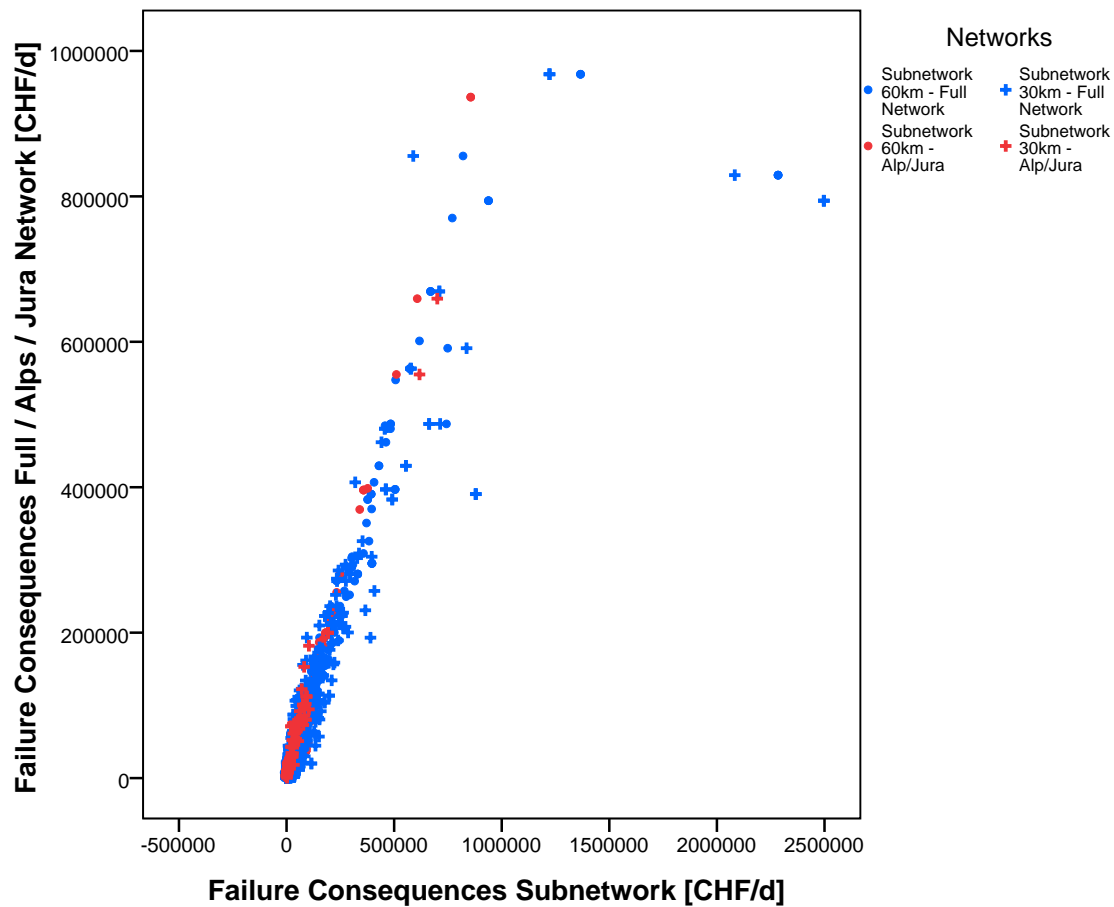
The additional travel distances are correlated with the additional travel time, especially for links in less dense parts of the network where the additional travel time is mainly determined by the detour length rather than influenced by local congestion. Hence, the correlation for links assessed with the Alps/Jura networks is substantially higher than for the full- or subnetwork approaches (Pearson coeff. 0.85 to 0.55/0.58, all highly significant at the 0.01-level) which also assesses densely populated areas. By dividing the additional distance by the additional travel time, one gets an indicator of the congestion effects caused by the link failure. Since the slowest free flow speed in the network, except for urban roads, is 50 km/h, congestion has a substantial influence on at least for those 12.4% of the cases with an average detour speed below this limit.

Considering the willingness to pay for travel time reduction ((Hess *et al.* (20)) of 21.3 CHF/h and the average cost of one traveled kilometer of 0.50 CHF (VSS (21)) the transport related failure consequences expressed as additional user costs can be calculated. The distribution of these costs shows exponential behaviour (Kolmogorov-Smirnov test statistic of 20.7) with an exponential value of $7.86 \cdot 10^{(-5)}$. The highest consequences are found for the Simplon and Gotthard north-south Alp tunnels with a loss of 1.3 and 1.1 million CHF/day respectively, followed by the motorway passing by Monte Ceneri (0.97 Mio CHF/day) which all are also served by rail tunnels. Also 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.

Accuracy of the Subnetwork Approach

As the majority of the links failure consequences are assessed with the 60km subnetwork methodology, it is important to confirm that the calculated failure consequences agree with the full network assessed consequences. For this reason, all links subject to the full and Alps/Jura-network approach were also assessed with the 30km and 60km subnetworks. Figure 2 shows a scatterplot comparison of the subnetwork and the full and the Alps/Jura network assessed consequences. 8 outliers from the 30km subnetwork are not included since these values extend beyond the scale of the figure. Except for some cases, the results calculated by the 30km and 60km subnetworks are very consistent with the full network results. The actual assessed consequence level is overestimated in these cases because the limited network does not cover all relevant detours. The small number of outliers and the low deviation from the reference values confirms that demand shifts are typically spatially restricted. This is mainly a product

FIGURE 2 Comparison between the 30km and the 60km subnetwork consequences against the full and the Alps/Jura network assessed traffic consequences



of the high network density and the short average path distances, which automatically restricts the spatial scale of the analysis. The outliers are the links representing the motorway leading through Ticino, which is characterized by steep mountains where only one relevant detour in near distance is available. This detour does not have the capacity to absorb all of the demand which is rerouted along to more distant detours which are not included in the subnetworks.

MODELING INDIRECT FAILURE CONSEQUENCES

Using the subnetwork approach, computation time to assess indirect failure induced traffic consequences across a national network is feasible. For the Swiss case, it takes around two weeks on a Pentium 4, 3.2GHz Processor with 1Gb RAM. However, knowledge of script programming and the availability of an assignment model is required to generate subnetworks thereby reduces its applicability. Hence, it would be desirable to assess traffic consequences more directly. One approach is to use a statistical model to estimate a link's indirect failure consequences. The statistical model combines spatial data and information of the link volume and estimates consequence influence coefficients for each parameter. Using the resulting parameters values one can indicate the magnitude of vulnerability without an assignment model.

Since the consequence measure follows an exponential distribution, the employed statistical model is a generalised linear model which assumes the dependent variable to be exponential distributed. The selection of the independent variables to determine the failure consequences was chosen to preferably match the little input data requirements, since it should be transferable to instances where no assignment model available. The results presented above showed large failure consequences for links with high volume, long detour distances or little network density. Therefore, the presented statistical model employed these factors but does not include any data that can only be derived from an assignment model like the average path distance.

The model combines the variables shortest detour, network density and volume. Additionally, as categorical variable, the network type with which each link's failure consequences were calculated were also included in the model. This additional information can also be seen as a proxy for the average path distance as shown in Table 1 but does not require assignment model derived information. Since in the calculation of the failure consequences the volume acts as multiplying factor, this variable was modeled as an interaction term. The categorical variables were employed as dummy variables in order to estimate separate parameters for links according the network type used in the prior consequence assessment. The data basis is built from link failure of all cases where each case had positive values of additional travel time and indirect failure consequences. The final model has the following structure:

$$CI_i = Const + \beta_{1,NT} * Dummy_{NT,i} * V_i * TD_i + \beta_{2,NT} * Dummy_{NT,i} * (V_i^2 / C_{5km,i}), \quad (5)$$

with

CI_i = Indirect failure consequences [CHF/day], derived from the assignment solution,

$\beta_{j,NT}$ = Parameter estimate for term j,

$Dummy_{NT,i}$ = Dummy network type used for the assessment,

V_i = Link volume [Vehicles/day],

TD_i = Travel time shortest detour [h],

$C_{5km,i}$ = Capacity * Length per km^2 of all links within a radius of 5km [$veh * km$].

In this model, the first term accounts for the intercept, the second term describes the shortest detour and the third term captures capacity limitation effects. During the modeling process other variables were also tested but this model proved to have the highest explanatory power while maintaining simple and transparent in its structure. The results presented in Table 2 affirm the earlier statement that traffic demand redistribution is assumed to be spatially restricted, as the included variables describe only the network part adjacent to the studied link.

The parameter for variable describing the shortest detour for links assessed the Alps/Jura network is very similar to the value of travel time savings indicating that demand is primarily

TABLE 2 Generalised linear model for indirect failure consequences

Parameter	β	Std. Error	Wald Chi-Square
Intercept	810.09	22.78	1265.05
Alp/Jura* V_i * TD_i	25.37	1.41	326.10
Full* V_i * TD_i	13.77	0.81	285.75
Subnetwork* V_i * TD_i	13.68	0.24	3315.68
Full* $V_i^2/C_{5km,i}$	0.38	0.04	100.84
Subnetwork* $V_i^2/C_{5km,i}$	0.26	0.03	96.23
$\rho^2 = 0.631, n=13'178$			

shifted from the failed link to the shortest detour. For links assessed in denser parts of the network, the additional potential of further detours reduces dependence on the shortest detour. The term quantifying capacity limitation effects for links assessed with the Alps/Jura network has been omitted since its effect proved to be insignificant. For links assessed with the full network, this term has a larger impact than for subnetwork links as congestion effects seem to be more crucial in case of failure of a motorway link. The distribution of the error term is normal (Kolmogorov-Smirnov test statistic of 38.719) fulfilling the need of the estimation methodology. The further analysis of the error term showed that the model is indeed able to predict the effective failure consequences for cases with low or moderate failure consequences but systematically underestimates the higher consequence cases with the highest values. These higher consequence links are characterised by having only one relevant detour in close proximity whose capacity is too little to absorb the rerouted demand. This specific characteristic is not adequately represented by the independent variables. These small number of predicted high failure consequences links, however, can easily be identified by checking the presence of local alternatives.

CONCLUSION

This paper presents an new approach for calculating transport related failure consequences including congestion effects across a national network. Failure consequences calculated using subnetworks are compared against those consequences assessed using the full network. The subnetwork methodology is an very accurate and reliable assessment approach as the rerouting effects tend to be spatially restricted around the failed link. Although it was expected that the spatial impact of a failure increases with longer path distances and shortest detour lengths, the results of the subnetwork approach are also very stable against these two factors. Only a few links required the use of the full or the Alps/Jura network.

Furthermore, by applying this analysis, one can identify for which links the traffic failure consequences are influenced by congestion. Only for limited number of links consequences are substantially influenced by congestion effects. However, the highest consequences are caused by congestion effects, since in these cases the costs of the additional travel time tends to be substantially higher as compared to the additional travel distance costs. Using the data presented in this paper, one could attempt to predict in advance which cases would require need of the inclusion of congestion effects thereby saving additional computation time.

Finally, by applying this methodology one can show how network structure influences failure consequences. These findings are especially valuable for case studies if no assignment model is available or if one is interested in identifying the links with the potentially largest traffic consequences for future detailed analysis.

The methods used in the paper do have some limitations which are potential topics of future research. The inclusion of the rail network as alternative detours could increase the accuracy of the methodology, especially for the case of Switzerland with its dense rail network. For this purpose, the user costs of a mode shift would have to be estimated, to which the results of present mode choice models could be applied. To avoid the calculation of a multi modal assignment, the rail network could be modeled as a overlaying (road) network with links connecting the two network layers and containing the respective mode shift financial costs.

Following the analysis on the initial network, links with no local alternatives were reanalysed to determine if any local non-considered link alternatives existed. However, this check was not systematically implemented beyond the high consequence links. Although it is assumed that negating these lower capacity roads does not induce significant bias in dense parts of the network, this assumption may have more influence in the mountainous regions of Switzerland, especially if alternatives detour paths around cut-links are not included. On the other hand, the presence of alternative routes in the mountainous parts may be assumed to be substantially smaller as these regions typically have smaller population densities and the higher construction costs in the steep terrain.

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 use genetic algorithms to identify link failure combinations which induce the most severe consequences.

ACKNOWLEDGMENTS

The authors gratefully acknowledge that this research was made possible through a grant from the Swiss National Science Foundation National Research Program 54: Sustainable Development of the Built Environment.

REFERENCES

1. Thompson, P., E. Small, M. Johnson and A. Marshall (1998) The pontis bridge management system, *Structure Engineering International*, **8** (4) 303–308.
2. Hajdin, R. (2006) KUBA Version 4.0, paper presented at *Conference on Operation and Maintenance and Rehabilitation of Large Infrastructure Projects, Bridges and Tunnels*, Copenhagen, May 2006.
3. Tyagunov, S., P. Heneka, L., J. Zschau, B. Ruck and C. Kottmeier (2005) CEDIM: From Multi-Hazards to Multi-Risks, paper presented at *Amonia Conference*, December 2005, <http://www.cedim.de/english/904.php>.
4. King, C. and R. Bell (2005) Technologies and trends for disaster monitoring and reduction, paper presented at *Earthquake Engineering in the 21st Century (EE-21C) conference: Technologies and trends for disaster monitoring and reduction*, Skopje, August 2005.
5. Federal Emergency Management Agency (2004) *Using Hazus-MH for risk assessment*, Federal Emergency Management Agency, Washington, D.C.
6. Schneider, S. H., S. S., P. A., I. Burton, C. Magadza, M. Oppenheimer, A. B. Pittock, J. B. Smith, A. Suarez and F. Yamin (2007) Assessing Key Vulnerabilities and The risk from Climate Change, in M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.) *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 779–810, Cambridge University Press, Cambridge.
7. Berdica, K. (2002) An introduction to road vulnerability: What has been done, is done and should be done, *Transport Policy*, **9**, 117–127.
8. Taylor, M. A. P. and G. M. D’Este (2003) Network vulnerability: an approach to reliability analysis at the level of national strategic transport networks, in D. E. Bell and Y. Iida (eds.) *The Network reliability of Transport , proceedings of the 1st International Symposium on Transport Network Reliability (INSTR)*, 23–44, Pergamon, Oxford.
9. Knoop, V. L., S. P. Hoogendoorn and H. J. van Zuylen (2007) Quantification of the impact of spillback modeling in assessing network reliability, paper presented at *the 86th Annual Meeting of the Transportation Research Board*, Washington, D.C., January 2007.
10. Matisziw, T., T. Murray and T. Grubestic (2007) Evaluating vulnerability and risk in interstate highway operation, paper presented at *the 86th Annual Meeting of the Transportation Research Board*, Washington, D.C., January 2007.
11. Bell, M. G. H. (1999) A game theoretic approach to measuring performance reliability of transport networks, *Transportation Research Part B: Methodological*, (34) 533–545.
12. Bell, M. G. H. and C. Cassir (2000) The n+m person game: Approach to network reliability, in R. S. P. Ltd (ed.) *Reliability of Transport Networks*, 91–102, Research Studies Press Ltd.

13. Chen, A., H. Yang, H. K. Lonad and T. W. H. (2007) A capacity related reliability for transportation networks, *Journal of Advanced Transportation*, **33** (2) 14–158.
14. Iida, Y. and H. Wakabayashi (1989) An approximation method of terminal reliability of road network using partial minimum path and cut sets, in W. Periodicals (ed.) *Transport Policy, Management and Technology towards 2001: Selected Proceedings of the Fifth World Conference on Transport Research*, 367–380, Ventura.
15. Jenelius, E., T. Petersen and L.-G. Mattsson (2006) Importance and exposure in road network vulnerability analysis, *Transportation Research Part A: Policy and Practice*, **40** (7) 537–560.
16. Knoop, V. L., M. Snelder and H. J. van Zuylen (2007) Comparison of link-level robustness indicators, paper presented at *3rd International Symposium on Transportation Network Reliability*, Delft, July 2007.
17. Scott, D. M., D. C. Novak, L. Aultman-Hall and F. Guo (2006) Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks, *Journal of Transport Geography*, **14**, 215–227.
18. Wardrop, J. G. (1952) *Some Theoretical Aspects of Road Traffic Research*, Institute of Civil Engineers.
19. Birdsall, J. and R. Hajdin (2008) Vulnerability assessment of individual infrastructure objects subjected to natural hazards, paper presented at *10th International Bridge and Structure Management Conference*, Buffalo, October 2008.
20. Hess, S., A. Erath and K. W. Axhausen (forthcoming) Joint valuation of travel time savings estimation on four separate swiss data sets, forthcoming.
21. VSS (2008) Kosten-Nutzen-Analysen (KNA) bei Massnahmen im Strassenverkehr , *Technical Report*, **SN 641 820**, Swiss Association of Road and Transport Professionals (VSS), Zurich.
22. Vrtic, M., P. Fröhlich, N. Schüssler, S. Dasen, S. Erne, B. Singer, K. W. Axhausen and D. Lohse (2005) Erzeugung neuer Quell-/Zielmatrizen im Personenverkehr, *Research Report*, Swiss Federal Department for Environment, Transport, Energy and Communication, Swiss Federal Office for Spatial Development, Swiss Federal Roads Authority and Swiss Federal Office of Transport, IVT, ETH Zurich, Emch und Berger, Institute for Transportation Planning and Traffic, Technical University Dresden, Zurich.
23. Vrtic, M., D. Lohse, P. Fröhlich, C. Schiller, N. Schüssler, H. Teichert and K. W. Axhausen (2007) Simultaneous two-dimensionally constrained disaggregate trip generation, distribution and mode choice model: Theory and application for a Swiss national model, *Transportation Research Part A: Policy and Practice*, **41** (9) 857–873.
24. PTV (2006) *Benutzerhandbuch VISUM 9.4*, Traffic Mobility Logistics (PTV), Karlsruhe.